CRWR Online Report 11-02

Water Planning and Management for Large Scale River Basins: Case of Study of the Rio Grande/Rio Bravo Transboundary Basin

by

Samuel Sandoval-Solis, Ph.D.

Daene C. McKinney, PhD., PE

May 2011

CENTER FOR RESEARCH IN WATER RESOURCES

Bureau of Engineering Research • The University of Texas at Austin
J.J. Pickle Research Campus • Austin, TX 78712-4497
This document is available online via World Wide Web at
http://www.crwr.utexas.edu/online.shtml

The Dissertation Committee for Samuel Sandoval Solis Certifies that this is the approved version of the following dissertation:

Water Planning and Management for Large Scale River Basins Case of Study: the Rio Grande/Rio Bravo Transboundary Basin

Committee:

Daene C. McKinney, Supervisor

Randall J. Charbeneau

David R. Maidment

David J. Eaton

Bryan R. Roberts

Water Planning and Management for Large Scale River Basins
Case of Study: the Rio Grande/Rio Bravo Transboundary Basin

by

Samuel Sandoval Solis, B.S.; M.S.

Dissertation

Presented to the Faculty of the Graduate School of

The University of Texas at Austin

in Partial Fulfillment

of the Requirements

for the Degree of

Doctor of Philosophy

The University of Texas at Austin

May, 2011

Dedication

Dedico esta tesis doctoral a Sil, mi amor, mi esposa, mi alma gemela, mi completo, mi fuerza, mi aliento, mi pasión; este esfuerzo te lo dedico a ti, agradezco infinitamente tu amor, paciencia y apoyo durante esta aventura llamada doctorado, ¡lo logramos!

A mis padres Jesús y Alicia, los dos son un ejemplo de vida para mi, los amo con toda mi alma

Acknowledgements

I would like to express my endless gratitude to my advisor, mentor and friend Dr. Daene McKinney for his wisdom, guidance, and support throughout my time at The University of Texas. Dr. McKinney provided me with the opportunity to venture into the fascinating field of water planning and management, transboundary basins and of course the Rio Grande/Rio Bravo, the basin that made us do research together, try to understand the incomprehensible (or at least look for some sense), do some traveling and have some successes and failures during the process; thank you for never made things easy, thank you for the discussions and insightful talks. I would like to thank Dr. David Maidment, Dr. Randall Charbeneau, Dr. David Eaton and Dr. Bryan Roberts for being members of my dissertation committee and for their word of encouragement along the way.

Special thanks to Carlos Patiño Gomez who shared his knowledge regarding the Rio Grande/Bravo and who helped me and my wife to establish in Austin, I will never forget his hospitality when we arrived, I appreciate his friendship. Also special thanks to Becky (Dr. Rebecca Lynn Teasley), she encouraged me to learn about the basin and modeling, we worked together in the same projects and become excellent friends, I am thankful for her support, expertise and friendship. In the last few years I have developed a nice friendship with Eusebio Ingol Blanco, he had become a person to talk and discuss not only things related with the Rio Grande/Bravo and climate change, but also other topics such as life, family, Latin America, among other stuff, I appreciate his friendship.

Special thanks are also given to my primary sponsorship CONACyT (Consejo Nacional de Ciencia y Tecnologia); this Mexican institution provided me all the financial resources during my PhD process, my endless gratitude with CONACYT. Also, partial funding was provided by U.S. Department of Agriculture, Instituto Mexicano de Tecnología del Agua (IMTA) and the World Wildlife Fund Chihuahuan Desert Program. Special thanks to Gregory Thomas from the Natural Heritage Institute who become an extraordinary friend of adventures as well as my external adviser in hydro-politics and decision making. Thanks to Hector Arias, he was also part of the outreach of results. Also special thanks to Jack Sieber and David Yates for their support using WEAP.

In this process I meet a lot of people from both countries, this is a list of people related to the Rio Grande/Bravo that helped me during my research and later some of them become friends; excuses in advance if I forget any person; from IMTA: Dr. Polioptro Martinez, Hector San Vicente, Alberto Guitron; from CONAGUA: Alfredo Galindo, Vicente Quezada, Doroteo Treviño, Amalio Cardona, Melchor Lopez, Mario Lopez, Rafael Rosales; from JCAS Chihuahua: Humberto Silva, from CILA: Dr. Roberto Salmon, Ramiro Lujan, Aldo Garcia, Gilberto Elizalde; from IBWC: Gilbert Anaya, Elizabeth Verdecchia; from TCEQ: Carlos Rubinstein, Stephen Niemeyer, Kelly Keel; and from TWDB: Mark Wenzel.

Very special thanks to the "Scientific International Committee for Environmental flows in the Big Bend", this is a high qualified scientific group that has become a nice circle where I have explored environmental policies and learned how to see things from different perspectives. I would like to give the thanks from USU: Jack Schmidt, David Dean; from WWF: Mark Briggs, Jurgen Hoth, Mauricio de la Maza, Alfredo Rodriguez, Amanda Cleghorn, Ivonne Muñoz, Norma Mendiola; from NPS: Jeffery Bennett, Raymond Skiles, Joe Sirotnak, from Env. Defense: Karen Chapman, from US FWS: Aimee Roberson, from CONANP: Carlos Sifuentes, and the rest of this amazing group.

Also I created an amazing group of friends that made my life at UT quite enjoyable, thanks to Bradley Eck, Eric Hersh, Stephanie Johnson and Angela Ronay, Paula Kulis, Ernest To, Shipeng Fu, Marcelo Somos, Fernando Salas, Dr. Pepe Salas, Laura Read, Fernando Almada, Natalia Ibañez, Hector Garcia, Sedat Yalcinkaya, Georges Comair, Gonzalo Espinoza, Benjamin Reith, Sardorbek Musayev among others. I am grateful for my friends Ryan Schmidt, Denise Landeros, Maria Elena Sanchez, Juan Carlos Novela, Mayra Meléndez, Giovanni Sosa, Carolina Lopez Espinosa and Javier Dorantes Perdomo.

Agradezco el apoyo, comprensión y amor de Sil, ella ha sido el pilar mas importante en este proceso de doctorado, gracias por escuchar mis inquietudes, éxitos y tropiezos, nada de esto hubiera sido posible sin ti. Te admiro mucho, gracias por estar a mi lado, gracias por ayudarme durante los momentos difíciles, gracias por soñar juntos. Agradezco especialmente a mis padres, Jesús y Alicia, por sus palabras de aliento, oraciones y apoyo, gracias por acompañarme durante mis múltiples visitas a México, siempre estuvieron en mis pensamientos a lo largo de este proceso, los dos son mis héroes, los quiero mucho. Gracias a mi Padrinovich y Madrinovich, Gonzalo Sandoval y María Antonia Muñoz respectivamente, gracias por escucharme, brindarme ánimos y consejos a lo largo de mi doctorado, gracias por formar parte de nuestra familia. Agradezco a Elvia Zamora por su apoyo, sus palabras de aliento, su compañía y consejos, gracias por sus visitas frecuentes a Austin, cada visita nos trajo vitalidad a nuestras vidas. Este trabajo es también en memoria de Miguel Almaraz Ovando y Álvaro Isidro Sandoval Sánchez, dos entrañables personas que extraño mucho.

Water Planning and Management for Large Scale River Basins
Case of Study: the Rio Grande/Rio Bravo Transboundary Basin

Publication No._____________

Samuel Sandoval Solis, Ph.D.
The University of Texas at Austin, 2011

Supervisor: Daene C. McKinney

Because water is not equitably distributed in time and place, in the right quantity with the adequate quality, water planning and management is used to redistribute the resource in such a way that tries to satisfy the necessities of water users, including the environment. Policies are proposed to improve the water management, however, selecting the best alternative can be difficult when tradeoffs among alternatives improve certain aspects of the planning and management and worsen others. This research establishes a methodology to evaluate water management policies in order to clearly and systematically identify policies that improve the water management. First, each water user, system or environmental requirement are evaluated using performance criteria. Second, performance criteria are summarized using the Sustainability Index. Finally, individual Sustainability Indices are grouped using the Sustainability by Group Index. The Sustainability by Group Index makes it possible to compare groups of water users and regions at a glance. This methodology has been successfully applied in the Rio Grande/Rio Bravo basin, a transboundary basin between the United States and Mexico. A set of scenarios was defined by water users, authorities and environmental organizations of the basin from both countries. A water resources planning model was constructed to represent the water management of the basin. The model was used to evaluate several scenarios and the benefits or damages that each policy provides. Two winning scenarios (called Meta-scenarios) that improve the management for water users, the environment and international treaty obligations were identified. Meta-scenario A is an immediate action scenario that includes: buyback of water rights, improvement in irrigation infrastructure, water demand reduction for irrigation districts in Mexico and the US, groundwater banking and the inclusion of environmental flows. Meta-scenario B is a short term scenario that includes the policies of Meta-scenario A plus expanded buyback of water rights, additional improvements in infrastructure and sharing of water savings between farmers in the US and Mexico. Results have been presented to decision makers and water users in both countries who will ultimately decide if they should implement the suggested policies. Most importantly, some alternative policies are now known that can help to improve the water management in the basin, for whom and where.

Table of Contents

List of Tables

List of Figures

Chapter 1 Introduction

1.1 Background

Because water is not equitably distributed in time and place, in the right quantity with the adequate quality, a discipline called water planning and management is used to redistribute the resource in a way that satisfies the needs of water users, including the environment. As a rule, water planning and management tries to meet the water requirements of all the water users, although, sometimes this is not possible. Frequently, conflicts among water users arise because water is a shared resource. The difficulties increase when the systems become large with numerous water users, several types of use, with unequal spatial distribution and such scarcity that water cannot be re-distributed without affecting other water users. Nowadays, this seems to be the common pattern of water allocation in large basins.

In transboundary basins, water planning and management is more complex. When possible, negotiations take place in order to define the sources, quantity, quality and timing of water to which each riparian has a right (Dinar et al. 2007). Typically, international basin commissions integrate country representatives to guarantee compliance with international agreements. In these basins, international agreements, local, federal and state regulations must be met, all at the same time. Problems in these regions arise in the coordination of all authorities, agencies and water users involved in the planning and management.

Water planning and management involves uncertainty in future events (Loucks and Van Beek 2005). In order to assess these uncertainties, several tools have been developed, such as simulation and optimization models. Models represent as accurately as possible the real water resource systems, but they also provide a tremendous amount of results that are not easy to interpret, especially in large basins. Selecting the best alternative can be difficult when tradeoffs among alternatives improve certain aspects of the planning and management and worsen others. It can be difficult to present an evaluation of a water resources system in a way that makes the selection of the best alternative easier and clearer.

1.2 Objectives

The goal of this research is to develop a methodology for evaluating water management scenarios for a large scale transboundary river basin. The objectives of this research are:

1. Construct, calibrate and validate a water resources planning model that represents the hydro-physical and regulatory framework of a large scale transboundary basin.
2. Define a methodology to evaluate and compare water management scenarios.
3. Utilize the water resources planning model and the methodology defined to evaluate alternative scenarios for improving water management in the basin.
4. Assess the water planning and management for the transboundary basin.

1.3 Dissertation Outline

This dissertation is divided into nine chapters. The scope and the objectives of the research are stated in the first chapter. The literature review of water planning and management in basins, transboundary basins and in the Rio Grande/Rio Bravo basin is presented in chapter two. Chapter three describes the methodology implemented to evaluate, summarize and compare results for different water management scenarios.

Chapter four describes the water management principles of the Rio Grande/Rio Bravo basin. Chapter five describes the construction calibration and testing of the water resources planning model built to simulate the water resources system. In chapter 6 the alternative water management policies to be evaluated are defined. Chapter seven presents the results of the scenarios analyzed. Chapter eight shows the results for "Meta-scenarios", which are a combination of scenarios that were identified as beneficial for the water management in the basin. Chapter nine provides the conclusions and recommendation of this research.

1.4 Contributions to the State of the Art

This research presents two main contributions to the state of the art:

1. *Synthesis of Results* –The methodology developed in this research allows the systematic evaluation of alternative water management policies (scenarios) for individual water users, groups of water users, regions or a whole basin that is under consideration. The results are stored and summarized in 3 different layers for different purposes and audiences. In the first level, *Performance Criteria* (Chapter 3.1) are stored for different water users, the environment or system requirements; in this level it is possible to analyze in detail the effects of each policy evaluated for each individual water user. In the second level, the *Sustainability Index* (Chapter 3.2.1) the results of the performance criteria are summarized for each water user, system or environmental requirement; in this level it is easier to compare different water management policies than at the water user level. Results of the previous two levels are focused on water users and water operators. In the third level, the *Relative Sustainability Index*

(Chapter 3.2.2) summarizes the results of the Sustainability Index; results are recapped by water users groups, regions and for the whole basin. In this level it is easier to compare different water management policies from the perspective of a water user's group, a region or the whole basin. Results from this level make it possible to identify areas of potential improvement and regions at risk. Results from this level are focused on water authorities and decision makers.

2. *Analysis of Scenarios* – The analysis of scenario evaluation results allows the systematic identification of policies that improve water management in the basin. This analysis is done in two steps. In the first step, individual or basic combinations of *Scenarios* (Chapter 7) are evaluated to identify their effects, quantify the magnitude of the benefits or drawbacks, and locate the areas of improvement or worsening; during this step the benefits and drawbacks for water users, the system and environmental requirements are identified. In the second step, the policies that provided more benefits are integrated into *Meta-scenarios* (Chapter 8), which are individual or combination of policies that provide additional mutual benefits for water users, system and environmental requirements than the individual scenarios.

These two contributions are graphically represented in Figure 1-1. Similar studies have analyzed a wide range of performance criteria without synthesizing results to identifying winning policies, such as average storage and releases (Vigerstol 2002, MRC 2004), total volume of water supplied to water users and to the treaty obligations (Orive-Alba 1945, Vigerstol 2002, Tate 2002, Gastelum et al. 2009), water supply in drought and normal conditions (Tate 2002), irrigated area (Gastelum et al. 2009, MRC 2004), minimum delivery, average annual supply, vulnerability and resilience (Teasley 2009) and reliability (Tate 2002, MRC 2004, Gastelum et al. 2009, Teasley 2009). Gastelum et al. (2009) and Teasley (2009) summarized their results in terms of monetary value and coalition value, respectively; however, none of the previous studies considered performance criteria to systematically synthesize the evaluation of benefits and the drawbacks for scenarios in order to assess, identify and construct policies that improve the water management in the basin.

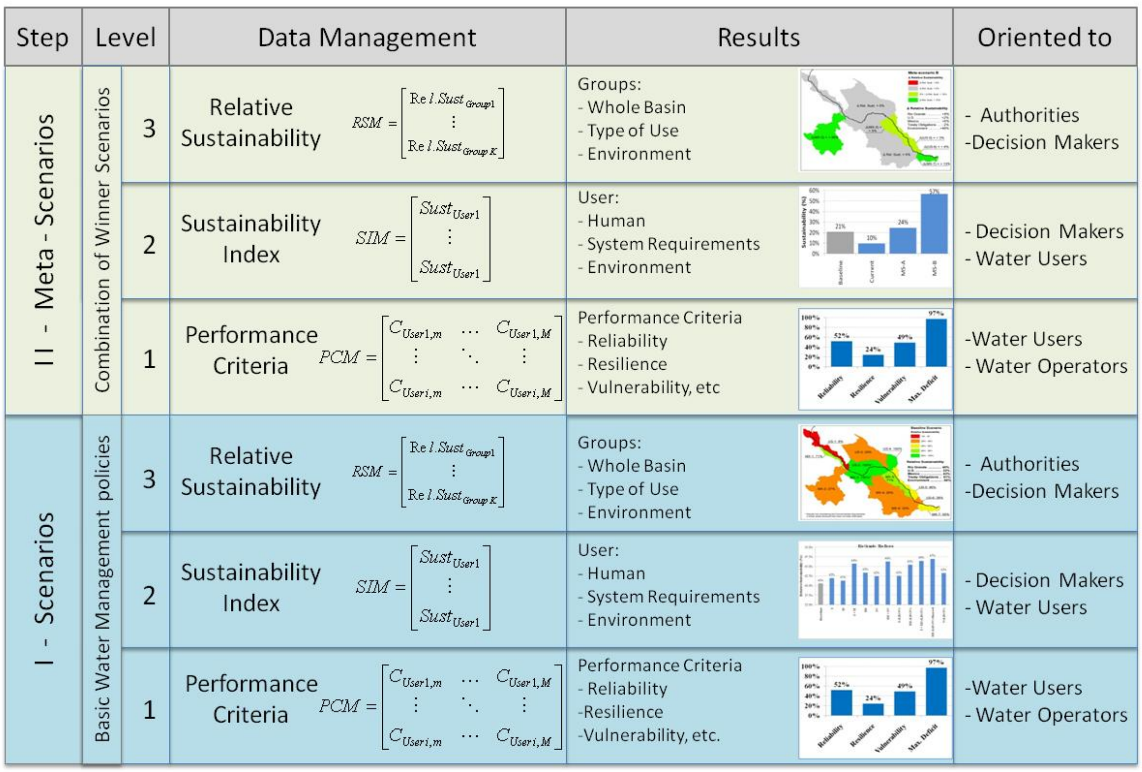


Figure 1-1: Synthesis of Results and Scenario Analyses

Chapter 2 Literature Review

In this chapter is presented the literature review of water planning and management in general, for transboundary basins and in the Rio Grande/Rio Bravo basin. The first section describes the literature review of water planning and management, sustainable water resource systems, integrated water resource management and decision support systems. The second section focuses in the Rio Grande/Rio Bravo planning and management; how it has evolved along time, challenges and current status of the basin.

2.1 Water Planning and Management

Too little, too much and too polluted water (Loucks 1981), too much ecosystem lost; these are the motivations of water planning and management. Reducing the adverse impacts of droughts, floods, excessive pollution and environmental degradation are the objectives of several planning and management exercises. Other goals include increasing water supply, hydropower, improving recreation, navigation and current policies to obtain more benefits. Finding the best social, economical and environmental way to manage the renewable yet finite and variable water resource, today and in the future, is the highest premise of water planning and management, in other words, designing sustainable water resources systems.

Water resources systems are integrated by the interaction between: (1) the natural hydrology, (2) the human development in the basin and (3) the legal/regulation system to administrate this resource. Basin's natural hydrology include: precipitation, evaporation, infiltration, runoff, rivers, lakes, aquifers, flood plains, deltas, estuaries, watersheds, soils, vegetation, fauna, ecosystems, geomorphology, geology, among others characteristics. Human development in the basin include: reservoirs, channels, infrastructure, water supply facilities, sewage systems, discharges, water treatment plants, irrigation districts, return flows, hydropower, pumps plants, recreation facilities, levees, flooding control facilities, among other facilities. The administrative system include: regulations, laws, operation and allocation rules, compacts, treaties, agreements and conventions, between water users, institutions, states, nations and the environment. Humankind use water to satisfy its requirements for consumption, food production, industry, recreation, energy production, health and sanitary purposes. How to meet human water requirements without compromising the environmental health of the ecosystems considering the current and future water availability in the basin? Water planning and management is a discipline that analyzes, proposes strategies and designs sustainable water resources systems to answer the previous question, in a broad sense, it deals with problems of water quantity and quality in basins.

Water quantity problems refer to challenges along the whole spectrum of hydrologic conditions: droughts, normal conditions and flooding. Drought problems are related to periods of water scarcity; how to operate the system to reduce, to the extent of possible, the negative effects on human and environmental requirements in dry periods? During normal hydrologic condition, problems are related to water allocation and system operation; how much water can be allocated to each stakeholder to obtain the most benefits without compromising the ecosystems' environmental health and the future availability of water? Flooding problems are related to the excess of water during short periods of time, which facilities and what strategies are needed to avoid damage for a determined flood event? Water quantity problems refer to issues related to intolerable water quality conditions for determined use, what kind of facilities and strategies are necessary to satisfy the water quality necessary to met environmental and human water requirements?

Several methodologies, philosophies and mathematical models have been proposed to address these questions. In some sense, these procedures represent the value that the society, governments, politicians, scientist and engineers gave to water, considering the social, economic and political context. In the 1800's and early 1900's, water planning and management was focused in designing systems that maximize the use of water and provide the most economic benefits for water users, while following the interests and vision of the respective country, agency or ministry. For instance, the objective of the water negotiations in the treaty of 1944 between the U.S. and Mexico was to maximize the use of water for agriculture purposes while providing an equitable allocation of water between both nations in the Colorado River and the Rio Grande/Rio Bravo (Enriquez-Coyro 1976, Orive-Alba 1945, Samaniego-López 2004). Primarily, water systems were designed to meet single purpose systems, agriculture and hydropower were the most common objective for systems designing. Development in the system was justifiable when the estimated cost was lower than the estimated benefits (USBR 1949). Later, systems started becoming more complex because constraints were imposed by existing law, international and interstate agreements, and the change from single to multi-purpose water systems. Typically, potential water uses considered were: irrigation, municipal and industrial, hydropower, flood control, minimum flow for navigation, recreational use and useful aquatic life (Maass et al. 1966). Given the new multi-purpose nature of the systems, research and study cases were necessary to determine water allocation that provided the most economic benefits; for instance the Tennessee Valley Authority case of study was the first large scale multipurpose river development (Ransmeier 1942).

In the 1960's, water planning and management focused in finding the design (infrastructure and operation policies) that maximize the net benefits of the system (Total

Cost – Total Benefits); in other words, the solution that provided the most economic benefits must be the executive design. Design of water resources systems were divided in four steps: identifying the objectives for the system, translating these objectives into design criteria (equations), propose several plans (scenarios) and evaluate the outcome for each of the plans. All scenarios were compared and the scenario that provided most net benefits was selected (Maass et al. 1966). In some sense, this philosophy considered the economic benefits as the driver of water systems' design, water users, authorities, decision makers and the environment must obey the outcome of this economic analysis. Some of the problems from the previous approach are: (1) not all benefits or cost can be easily expressed in economic terms, the most significant example is the cost/benefit of environmental degradation/conservation; (2) legal/regulatory constraints must be taken into account and not ignored for the sake of maximum economic net benefit, and (3) it is important who pays and receives the benefits; water users, decision makers and the environment matter (Loucks et al 1981).

In the 1980's Loucks et al. (1981) saw the water planning and management as a discipline that goes beyond the economic value of a system; water systems are influenced also by social, environmental, and political (institutional) objectives. By this time, authorities, water users, society, conservationist and politicians took a more active role in the planning process. Water resources engineers change their role from water planning dictators to a more democratic position, they were in charge of hearing, understanding and addressing (to the extent of possible) the necessities of different groups, and then presenting a set of best decisions to a water planning council, where decision are made. This approach revolutionized water planning and management philosophy, from finding the maximum net benefit, to identifying best feasible decisions (policies) given the social, economical, environmental and political (institutional) requirements, considering the natural and legal restrictions of the system (Loucks and van Beek 2005).

2.1.1 Transboundary Water Planning and Management

About 60% of the global freshwater flow is generated in 263 international river basins (Figure 2-1); these transboundary basins cover nearly one half of the of the earth's land surface where over forty percent of the world's population live (Giordano and Wolf 2002, UN 1978). Water management in transboundary basins is more complex; it is more difficult to identify the best water management that balance human and environmental requirements when there are interests of several nations; and concepts of sovereignty (Harmon 1895), cooperation and equity (Oppenheim 1928, Bogardus 1964), appropriative or riparian water rights (Burnes and Quirk 1979) are considered and discussed during the water planning process.

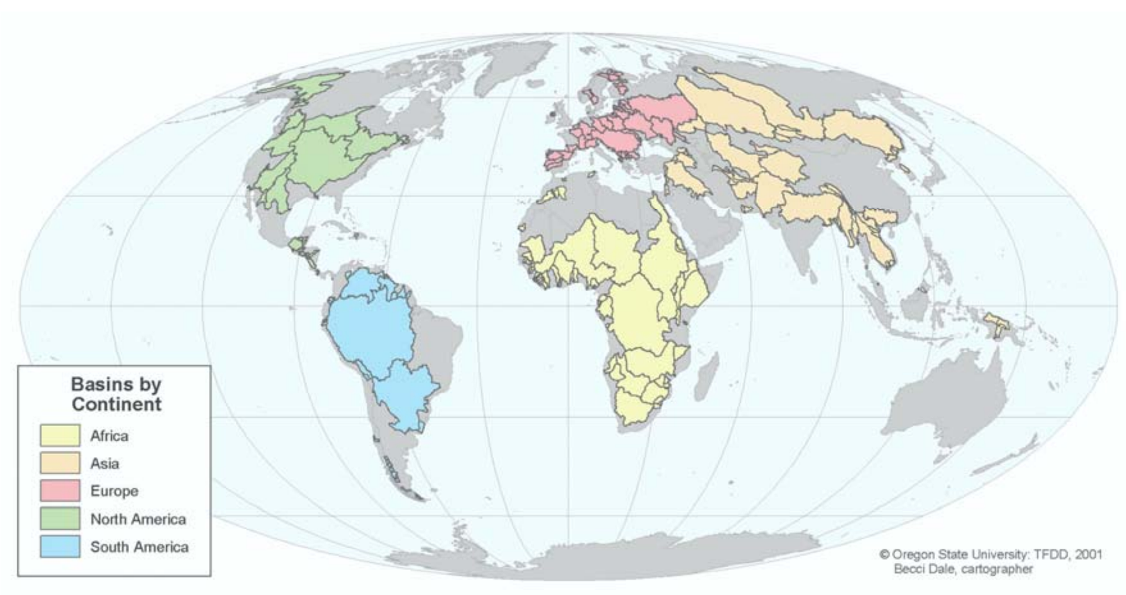


Figure 2-1: Transboundary River Basins (Source: Atlas of International Freshwater Agreements, Wolf 2002)

Sovereignty is a concept regarding the unrestricted exploitation of nation's natural resources, including water, within its own territory (Harmon 1895). This concept has been attempted/used in transboundary basins during unilateral actions in water developments projects. For instance, unilateral actions of Turkey have affected Syria and Iraq; the Great Anatolia Project undertaken by Turkey have used and diminished the streamflow for both downstream countries (Lupu 2002, Czekanski 2005). On the contrary, cooperation and equity are concepts regarding the necessity to set common ground and allocate water between nations fairly and reasonably (Dinar et al. 2007), for instance, the treaty of 1944 between the U.S. and Mexico shows the spirit of both nations to reasonably and fairly allocate the waters of the Rio Grande/Rio Bravo, Colorado and Tijuana rivers (Enriquez-Coyro 1976, Samaniego-Lopez 2004).

In addition, nations have argued appropriative water rights, "first in time, first in right", claiming the long usage of river's water before other riparian nations and as a consequence, the right to use the same amount of water in the future in spite of the harm this can cause in the economic development of upstream riparian countries. For instance, Egypt used its water right seniority in the Nile River during negotiations of the 1929 Nile Waters Treaty (Nile 1929), the 1959 Nile Waters Agreement (Nile 1959) and lately in the Nile Basin Initiative (NBI 2002). On the other hand, nations have argued riparian water rights (Enriquez-Coyro 1976); claiming that each riparian country has the right to take water for reasonable use regardless of the location in the basin (upstream or downstream), i.e. Ethiopia has claimed this concept in the Nile river, given that the Blue Nile that originates in this country provide about 85% of the water flowing into Egypt (Dinar et al. 2007).

Another catalyst for water conflicts and agreements is the natural water scarcity of transboundary basins. In the Rio Grande/Rio Bravo, the scarcity of water in the 1880's and 1890's derived in the 1906 Convention between the U.S. and Mexico, which is an agreement to allocate water in the El Paso/Ciudad Juarez valley. Dinar and Dinar (2005) showed that in two-riparian basins, scarcity is the key issue that drives the cooperation process. Figure 2-2 shows the water stress in transboundary basins (Wolf 2002), the Rio Grande/Bravo Basin is one of the most stressed basins in the world, less than 500 cubic meters are available per person per year.

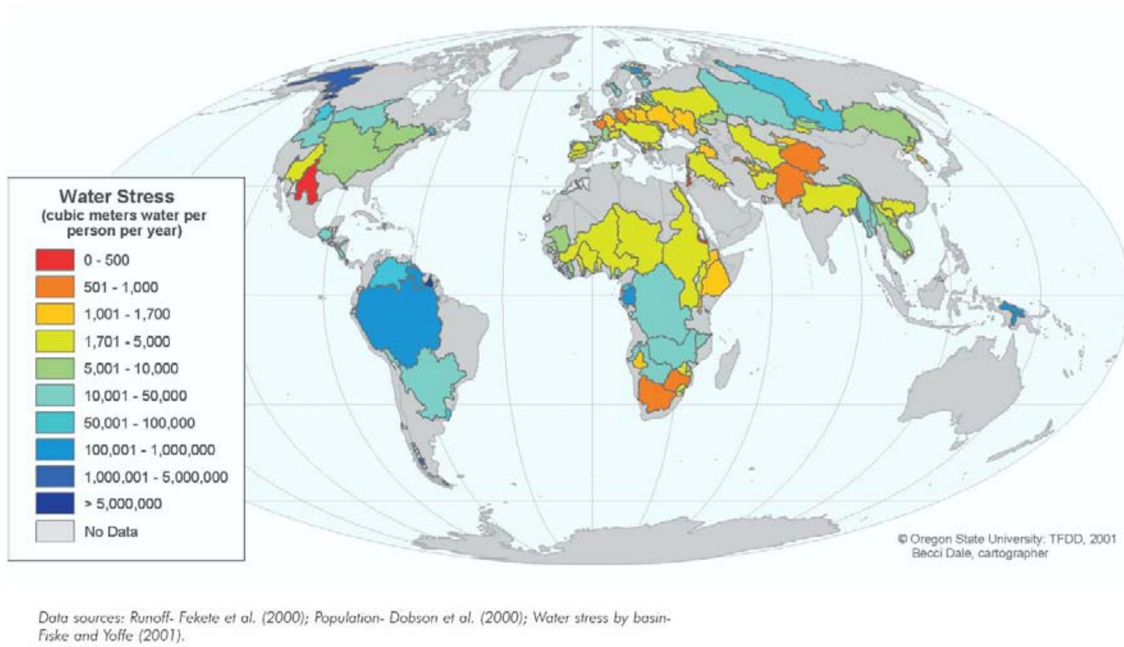


Figure 2-2: Water Stress in Transboundary Basins (Source: Atlas of International Freshwater Agreements, Wolf 2002)

In order to provide guidance and to avoid conflicts between nations, the international community has developed principles for transboundary water resources. In 1966, the Helsinki rules outline the basic principles for an equitable utilization of water in international rivers and the commitment not to cause any harm to basin states (ILA 1966). In 1997, the United Nation Convention on the law of the non-navigational uses of international watercourses (UN 1997) further defined the concepts of "equitable and reasonable utilization and participation" of international water courses as well as the "obligation not to cause significant harm" that were undefined on the Helsinki rules. In addition, regional agreements provide guidance in international water share and management. The European Union agreed two conventions: (1) the convention on environmental impact assessment in a transboundary context (UNECE 1991), in order to prevent adverse ecosystem's impact between riparian nations, and (2) the convention on the protection and use of transboundary water courses and international lakes (UNECE 1992), this agreement provide further provisions for monitoring, research assistance and water management protecting basin's ecosystems. Similarly, the Southern African Development Community agreed the protocol on shared watercourse (SADC 2000), this protocol is a regional adaptation of the UN Convention (UN 1997).

2.1.2 Sustainable Water Resources Systems

It has been 30 years since the concept of "*Sustainable development*" was for the first time introduced by the World Conservation Strategy (IUCN 1980). Sustainable development balances the exploitation of the natural resources, technology development and institutional change, in order to enhance the potential to meet human needs and aspirations, now and in the future (WCED 1987). Loucks (1997) defined sustainable water resources systems as "*those systems designed and managed to contribute fully to the objectives of society, now and in the future, while maintaining their ecological, environmental and hydrological integrity.*"

Part of the complexity of the sustainability concept lies in the uncertainty of: (1) necessities, wishes and requirements of future's society; and (2) future climate conditions and thus, future basin's hydrology. The only certain about future is a constant change in climate conditions and water requirements (IPCC 2007a). How to deal with this uncertainty? According to IPCC (2007b), system's adaptation is key to deal with this uncertainties; it is necessary to define adaptive policies that are flexible enough to supply more frequently water requirements (more reliable), reducing deficits in water supply (less vulnerable) and recovering faster from deficits (more resilient) given a change in climate conditions (Bates et al. 2008, Brekke at al. 2009). Adaptive management policies are those strategies designed to adjust to changing conditions given new information in water requirements or forecasting of future climate conditions. Thus, *Sustainable water resources are those systems designed and operated using adaptive policies that make the system more reliable and resilient, less vulnerable, considering uncertainty in future climate conditions and water requirements*. Because of this, the sustainability of a basin is also a measure of its adaptive capacity to current and future conditions.

2.1.3 Integrated Water Resources Management (IWRM)

The concept of Integrated Water Resources Management (IWRM) started appearing in the 80's (Biswas 1981) and it has been evolving primarily as a consequence of two conditions: (1) an increasing pressure on water resources caused by growing population and energy requirements, socio-economic developments, and environmental protection; and (2) designing of water resources systems migrated from a centralized, supply-oriented and engineer-bias approach, to an inclusive multi-sectoral, demand-oriented and multi-disciplinary approach, often called integrated water resources management (Loucks and van Beek 2005).

According to the Global Water Partnership (GWP 2000), "*IWRM is a process which promotes the coordinated development on management of water, land and other related resources, in order to maximize the resultant economic and social welfare in an* *equitable manner without compromising the sustainability of vital ecosystems.*" This process must be a participatory exercise involving water users, planners, NGO's, scientist, operators and decision makers at all levels, the aim is to consider all perspectives and ideas during the definition of the water management. Consequently, everybody included in this process feels important part during the definition, operation and evaluation of water management policies.

The objectives of IWRM include: (1) provide a forum where all people and institutions involved in water management can express and hear other's opinions, express concerns, complaints and solutions regarding this share resource, making water management a more transparent and inclusive process, (2) establish what is the definition of "sustainable water resource system" for the basin, what are the objectives to achieve? (3) define laws, regulations and rules to allocate water, establish priorities, protect the environment according to the objectives defined; (4) provide mechanisms to evaluate and modify (if necessary) current and future water management of the basin, making water planning and management a continuous adaptive process.

Let's define the relation between sustainable water resources systems, adaptive policies and integrated water resources management (IWRM). Designing sustainable water resources system is the highest premise in water planning and management; in order to achieve this goal it is necessary to identify adaptive policies that deals with different climate conditions and changing water demands. Basin models are used to simulate water resources systems, considering the natural hydrology, human development and the administrative water allocation system in the basin. Models are used to test different policies, they help in determining adaptive policies; which policies, or combinations of those, are necessary to make the system sustainable: more reliable and resilient, and less vulnerable, compared to the current system. Integrated water resources management is the process of bringing together all the people involved in the water management of the basin (water users, authorities, scientist, environmentalist and decision makers) to discuss and define what is the meaning of “sustainable water resource system“ for the basin; in other words, what are the goals to achieve. These goals include benefits for the economy, environment and society. For each of these goals, a series of performance criteria is necessary to evaluate and compare different water management policies. Several adaptive policies may reach the goals established in the definition of “sustainable water resource system”; during the IWRM process it is selected which of these policies should be chosen based on a consensus among the people included in the IWRM process. Notice that during the IWRM process is considered at all times the necessity to improve the welfare of society and the water resource system.

2.1.4 Decision Support Systems (DSS)

Nowadays, it is acknowledge the relationship between decision-making and the society’s potential improvements/worsening in their economy and quality of life, as well as environmental degradation/conservation. Decisions making in water management affect the environment, economy and social welfare of the people inside and outside the basin; water users upstream and downstream; water quantity, quality and its seasonal distribution; water storage in reservoirs and aquifers; surface and groundwater availability; among others aspects. Any proposed policy will have consequences in water supply for the rest of water users; thus, it is necessary to consider the environment and include stakeholders during the decision making process because they must negotiated their requests and compromise with the agreements taken (Loucks and van Beek 2005). During the planning, management and decision making process, it is useful to know the consequences of possible decisions to be made (Georgakakos and Martin 1996). This information is valuable to those responsible for choosing the best decision; it helps the understanding of expected outcomes of the decisions taken. DSS are interactive mathematical and computational models that represent the natural system whose objective is to quantify, evaluate and compare the benefits and worsening of different water management policies (Labadie and Sullivan 1986).

DSS do not solve the problem of finding the "best management" by themselves; they are tools that facilitate the evaluation of different management policies and their consequences; DSS help the understanding of different strategies and their outcomes. Ultimately, decision makers will decide the water management of the system considering the information provided by the DSS. Also, it is not enough to properly represent the natural and regulatory systems to administer water through DSS; results must be presented to people involved in the planning and management process, when solutions are needed, in an adequate format, accessible and understandable to these people and the community. DSS should provide a set of solutions during the window of opportunity when there is an interest in determined issue; if not, results will not have any impact in water management (Loucks and Da Costa 1991). Additionally, decision makers and water users should have confidence and trust in DSS results. For this purpose, it is necessary a close relation between the modeler, decision makers and water users during the DSS construction. Participation, supervision and feedback from the people involved in the water management process are needed to built trust and confidence on the DSS and its results, this exercise provide a shared vision of how the water system works.

DSS can be a single or multiple systems, all of them integrated by using an interface that allows the interaction between the user(s) and system(s). DSS can be integrated by the following systems: a) *measurement*, for instance remote sensing and in situ measurements; b) *information*, including geographic information systems and databases; c) *models*, such as economic, hydrologic, planning, optimization, holistic, empiric models; and d) *analysis*, such as evaluation, performance and diagnostic tools (Loucks and van Beek 2005).

Because of the improvements in computer calculation capacity in the last two decades, DSS have been used more frequently to represent water systems and evaluate alternative water management policies. Programs such as AQUATOOL (Andreu et al. 1996), RIBASIM (Delft Hydraulics 2004), MIKE-BASIN (DHI 1997), MODSIM-DSS (CSU 2011), OASIS (HydroLogics 2009), RIVERWARE (Zagona et al. 1998), WRAP (Wurbs 2005), STELLA (Palmer 2010), WEAP (Raskin et al. 2001, Yates et al. 2005a and 2005b); among others, have been used as the foundation of DSS in different basins.

DSS have been constructed for several transboundary basins; in America for the Colorado river (Schuster 1989, Gilmore et al. 2000), Rio Grande (Vigerstol 2002, Tate 2002, Brandes 2004, Danner et al. 2006, Teasley 2009), Columbia (Dufournaud 1982, Rogers 1991) and Red River (Simonovic 1999); in Asia for the Mekong (Dufournaud 1982, Baran and Coates 2000, MRC 2004), Ganges-Brahmaputra (Rogers 1993, Salewicz and Nakayama 2004), Amu Darya and Syr Darya rivers (Raskin et al. 1992, Savoskul et al. 2003, Teasley and McKinney 2011); in Africa for the Nile (Rogers 1969, 1991 and 1993, Georgakakos 2007), Congo (McCartney 2007), Zambezi (Salewicz 1991), Volta (De Condappa et al. 2009) and Okavango (EPSMO-BIOKAVANGO Eflows Team 2009); in Europe for the Danube (Salewicz 1991, Mauser and Ludwig 2002), Rhine (Nieuwkamer), Guadiana (Sorisi 2006) and Tagus (Andreu et al. 1996). In addition, DSS have been built for different basins, for instance in Spain for the rivers Segura (Andreu et al. 1996), Manzanares (Paredes et al. 2010); in Ireland for the Moy basin (Hall and Murphy 2010), in Peru for the Rio Santa (Pukey and Escobar 2009, Read and McKinney 2010); in the U.S. for the upper Chattahoochee river (Johnson 1994), Trinity, San

Joaquin, San Francisco Bay and Delta (Cain et al. 1998), Sacramento (Purkey et al. 2008, Yates et al. 2009), Sierra Nevada (Mehta et al. 2008, Viers et al. 2009); in Mexico for Rio Conchos (Wagner and Vaquero 2002, Gomez et al. 2005, Amato et al. 2006, Gastelum et al. 2009), Rio San Juan (Sandoval-Solis 2005), Rio Lerma (Vargas et al. 2004), Rio Verde (Sandoval-Solis 2009.a), Rio Copalita (Sandoval-Solis 2009.b), just to mention a few.

2.2 Rio Grande/Rio Bravo Basin

2.2.1 Introduction

The Rio Grande/Rio Bravo basin is a transboundary basin between the United States (U.S.) and Mexico (Figure 2-3). It is a fundamental resource for the economy, environment, health and quality of life for people in both countries and along the border. Cities, such as Albuquerque, Las Cruces, El Paso, Brownsville and McAllen in the U.S., and Monterrey, Ciudad Juarez, Saltillo, Chihuahua, Matamoros and Reynosa in Mexico depend on the water resources of this basin. The important agriculture economies of the El Paso/Juarez valley, the lower Rio Grande valley and the Rio Conchos irrigation districts also depend on the waters of this basin. The environmental health of the Big Bend National and State Park in the U.S. and the protected areas of Cañón de Santa Elena, Maderas del Carmen and Ocampo in Mexico are affected by the quantity, quality and timing of the Rio Grande/Rio Bravo streamflows. In addition, international obligations under the United States – Mexico Convention of 1906 and the Treaty of 1944 apply for both countries (IBWC 1906 and 1944). In this research, attention is focused on the middle and lower part of the basin, from Elephant Butte dam in New Mexico to the mouth of the Rio Grande/Rio Bravo at the Gulf of Mexico.

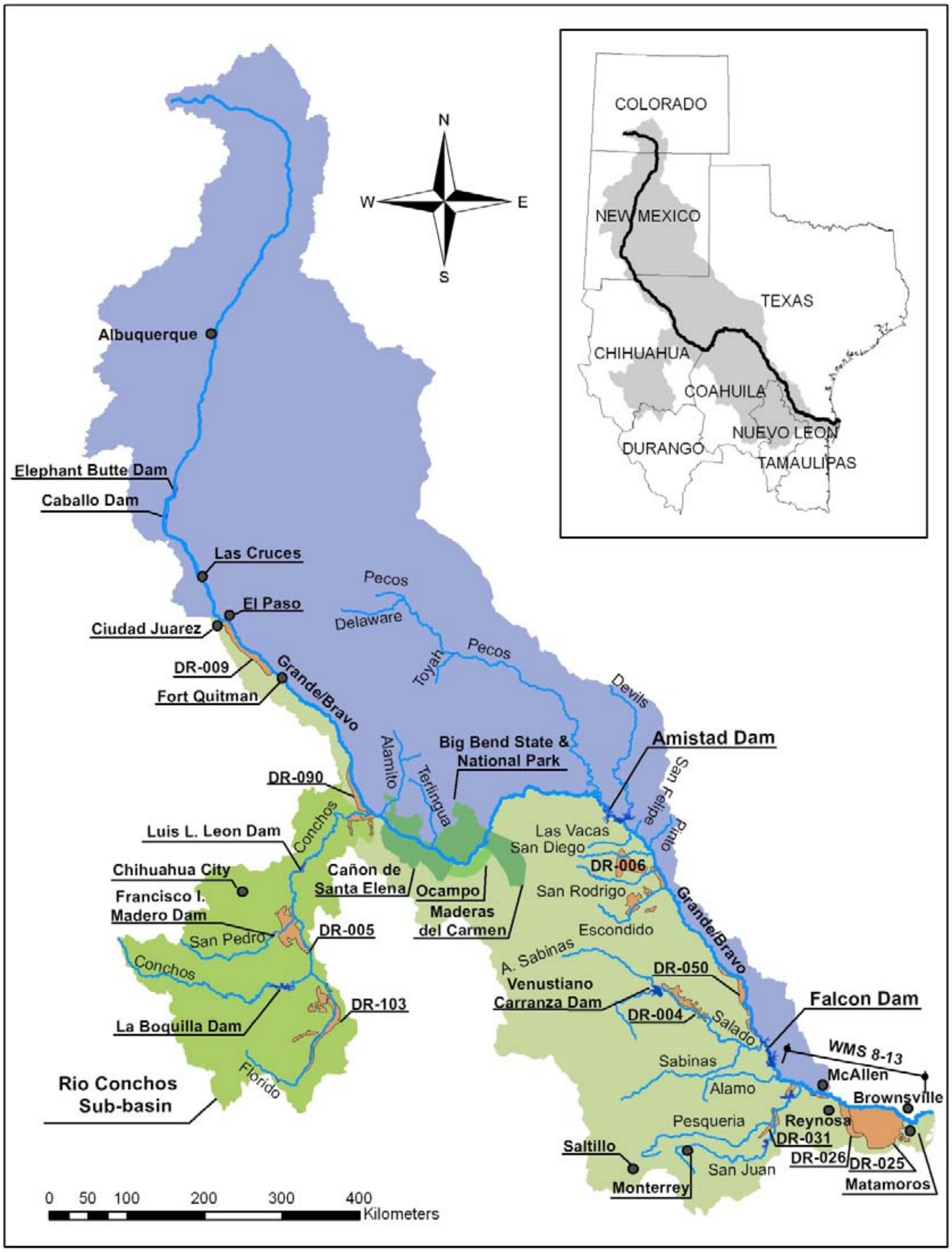


Figure 2-3: Rio Grande/Rio Bravo Basin

2.2.2 Background

Before the discovery of America, there is evidence that indigenous people used the waters of the Rio Grande/Rio Bravo. In 1584 Spanish settlers found indigenous inhabitants in the confluence of the Chama River and the Rio Grande/Rio Bravo, in what is now Espanola city, New Mexico (Mills and Follett 1898). In Franklin/Paso del Norte valley (which later become El Paso and Ciudad Juarez after 1889) there is evidence that in 1600's, indigenous inhabitants used to build a temporal weir (made form tree branches, rocks and mud) to divert the water from the mainstream to their orchards (Enriquez-Coyro 1976). In 1805, Alexander Humboldt (1966) described the crops grown in this region (corn, wheat, grapes) and the construction of the temporal weir. Similarly, indigenous inhabitants used the Rio Grande/Rio Bravo waters for agriculture purposes in Presidio del Norte (Presidio, TX), Presidio de Rio Grande (Rio Grande City, TX), Laredo and Refugio (Brownsville TX.) (Enriquez-Coyro 1976).

In 1836 the Rio Grande/Rio Bravo became a transboundary basin after Texas' independence in the San Jacinto Battle (William 2004). After that, there were border disputes between both parties, Texas and Mexico claimed the border at Rio Grande/Rio Bravo *del Norte* and Nueces rivers, respectively. After two failed attempts, in 1845 the Republic of Texas annexed to the United States of America (Fehrenbach 2000). The border issues will become important after Texas's annexation, which ultimately led into the Mexican war (1946-1948). The Guadalupe-Hidalgo treaty settled this dispute between both countries and defined the Rio Grande/Rio Bravo *del Norte* as the border (IBWC 1848). Later, in 1854 the Mesilla treaty (Gadsden Purchase) was the agreement that defined the border between both countries as it is now. In the Guadalupe-Hidalgo treaty was specified a navigability clause (Article VII) for the Rio Grande/Rio Bravo, this clause drove some of the proposals and infrastructure designs of the river until the signature of the treaty of 1944 (IBWC 1944) when this clause was nullified.

Since the signature of the Guadalupe-Hidalgo treaty in 1848 until 1877, water related problems were minor in the Rio Grande/Rio Bravo basin (Enriquez-Coyro 1976). In 1878, when Coronel Hatch was prosecuting bandits in the El Paso region, he noticed problems of water allocation during drought periods in this region (Hatch 1878). The same year, U.S. president Rutherford B. Hayes signed the Desert Land Act promoting the economic development of arid regions in western U.S.; offering land to people for a very small price with the only condition to irrigate the land bought for at least 3 years (Ganoe 1937). This act promoted a disproportioned expansion of agriculture land and water consumption in Colorado and New Mexico from 1878 to 1896, leading to water scarcity problems in the El Paso/Ciudad Juarez region. The previous situation was aggravated with an eight year drought (1877 - 1884). In 1880 is dated the first international complain regarding water allocation in El Paso/Ciudad Juarez region (Enriquez-Coyro 1976).

Because frequent problems of water allocation, constant channel changing (and thus changing of the boundary), and the poor delineation of the boundaries in land, in 1889 it was established two International Boundary Commissions (IBC), one commission who decides about water course changes and hydrologic problems, and another one for boundary delineation. The IBC was extended indefinitely in 1900 and is the considered the predecessor of the International Boundary and Water Commission (IBWC) who was established later, in 1944 (IBWC 2010).

Approximately since 1900's, the states of Colorado (1882), New Mexico (1898) (Corbridge and Wilkinson 1985) and Texas (1913) (Hutchins et al. 2004) used the prior appropriation system to assign water: "first in time, first in right". In Texas, after the 1950's drought the allocation system changed to a riparian system only for the Rio

Grande/Rio Bravo basin; in order to prioritize domestic, municipal and industrial use above irrigation and mining (Yoskowitz 1999). In Mexico, riparian system applied since the Spanish colonization (Enriquez-Coyro 1976), allocating water based on the type of use, domestic and municipal use have higher priority than agriculture or industrial water use. Before the Convention of 1906 there was no formal water management in the basin; water was allocated locally, based on the availability of water and agreements between water users (Corbridge and Wilkinson 1985).

2.2.2.1 Convention of 1906

Because of the continuous scarcity of water resources in the Rio Grande/Rio Bravo after 1887, and the increasing difficulty to achieve agreements in the El Paso/Ciudad Juarez region, a set of negotiations took place to define the water allocation between both countries in this region, ending with the signature of the Convention of 1906.

Since 1887, several negotiations and actions took place to define the method to divide water between both countries. Among the proposals, two are remarkable because of their historic importance and opposition: (1) Mills and Garfias (engineers of the IBC) proposed the construction of an international dam at El Paso dividing the water one third for the U.S., one third for Mexico and one third for the river, the share of the river was considered because of the navigability clause in the Guadalupe-Hidalgo treaty; and (2) Powel (USGS director) proposed supplying water to agriculture users in Colorado and New Mexico in order to maximize the irrigated area, and that after these appropriation, there would not be water left for senior water rights at El Paso region and thus; the necessity to eliminate the agriculture in this area (Enriquez-Coyro 1976).

Similarly, two doctrines of international water law are also remarkable because of their opposition: Harmon and Vallarta. In 1890, Mexico's general attorney Ignacio Vallarta proposed: (a) water must be divided in halves between both countries; (b) navigability of the Rio Grande/Rio Bravo clause defined in the Guadalupe Hidalgo treaty was violated because of the diversion of water in Colorado and New Mexico; (c) Powell's project not only accept the U.S. appropriation system but also, simplifies the problem to maximize the U.S. irrigated area; (d) Mexico has the right not only to stop the U.S. diversions, but also to revoked the existing water rights; and (e) Mexico has the right to claim for a compensation (Enriquez-Coyro 1976). On the contrary, in 1895 U.S. general attorney Judson Harmon proposed the absolute sovereignty doctrine: "*The fact that there is not enough water in the Rio Grande for the use of agriculture does not give to Mexico the right to subject the United States to burden of arresting its development and denying to its habitants the use of a provision which nature has supplied, entirely within its own territory. The recognition of such a right is entirely inconsistent with the sovereignty of the United States over its national domain."* Lately, Harmon expressed that the solution of the conflict will be the negotiation of a treaty with Mexico and not the unilateral position he expressed initially (Samaniego-Lopez 2004).

During 1887 until 1904 two main projects were discussed: (1) the Elephant Butte dam project in New Mexico property of the Rio Grande Dam & Irrigation Company and (2) Mills' dam proposition in El Paso/Ciudad Juarez. In 1902 was published the Reclamation Act that funded irrigation projects for the arid lands of 17 states in the American West. In 1904 the Reclamation Service took control of the situation in the El Paso/Ciudad Juarez region and the following year the Reclamation Service and the US Geological Survey defined the first draft of what later became the Convention of 1906. The project consisted in the construction of Elephant Butte reservoir and the distribution of water to irrigate 97,000 acres in New Mexico, 53,000 acres in Texas and 25,000 acres in Mexico. The water was distributed as follows: 55% to New Mexico (233,000 acre-foot- 287 million m^3/year), 30% to Texas (127,000 acre-foot- 157 million m^3/year) and 15% to Mexico (60,000 acre-foot - 74 million m^3/year). The Convention of 1906 established the water management rules in the Rio Grande/Rio Bravo from Elephant Butte dam in New Mexico to Fort Quitman, Texas.

2.2.2.2 Treaty of 1944

The Convention of 1906 only alleviated the problems along the Rio Grande/Rio Bravo between El Paso/Ciudad Juarez to Fort Quitman, Texas. Conflicts between the United States and Mexico were recurrent about water distribution in the Rio Colorado and Rio Grande/Rio Bravo.

In the Rio Colorado, in the early 1900's up to 1922, water conflicts involved the distribution of water within seven states and Mexico, water distribution for the Imperial irrigation district and frequent floods in the mouth of the river at the Golf of California (Enriquez-Coyro 1976). In 1922 the seven states signed the Colorado River Compact allocating the water between the upper (Wyoming, Colorado, Utah and New Mexico) and lower (California, Arizona and Nevada) basin states (DOI 1922). While the Colorado River Compact established the overall rules of water allocation within the U.S., the water conflicts with Mexico were still unsolved.

Meanwhile in the Rio Grande/Rio Bravo, the agriculture in the basin prospered. The lower Rio Grande valley, (McAllen-Brownsville/Reynosa-Matamoros area) grew in the agriculture land from 5,000 hectare in 1908 to 154,000 hectare in 1935. At this location it was estimated that two thirds of the water came from Mexican sources. In addition, the variability of the water resources made impossible the full utilization of the river, sudden floods were followed by extended periods of drought. The necessity to control and regularize the river was evident if further development in the agriculture sector was expected (Enriquez-Coyro 1976).

Non water factors delayed the negotiation of an international agreement that would solved the water conflicts between both countries. The Mexican Revolution (1910-1921) and the First World War delayed the negotiations for a decade. In the 1920's and early 1930's, several meetings and informal negotiations took place about water distribution of the Colorado, Tijuana and the Rio Grande/Rio Bravo waters. During this period the conflicts moved around the negotiation of all basins at the same time and the amount of water compromised to deliver for both countries. The relationship between both countries was very distant and tense from 1936 to 1939, Mexico started commercial exchange with the axis powers and in 1937 the Mexican government nationalized the oil industry from U.S. companies. Conciliation meetings happened in 1939 to negotiate the compensation terms for U.S. companies due to the oil industry nationalization. The same year the Second World War started, the United States entered the conflict in 1941 after the Japanese bombing of Pearl Harbor, and Mexico declared the war on the axis powers in 1942.

The negotiations for 1944 Treaty started in 1940. A full hydrologic study of the Colorado and the Rio Grande/Rio Bravo was done to examine the best agreements for both countries. Meanwhile in the Colorado the negotiations moved around the amount of water delivered from the U.S. to Mexico; in the Rio Grande/Rio Bravo the situations was the opposite, the negotiations focused on the amount of water delivered from Mexico to the U.S. This unique condition where in one basin (Colorado) one country was the upper riparian and in the other basin (Rio Grande/Rio Bravo) the same country was the lower riparian, made possible a fair discussion of the treaty terms. It was impossible to be negligent in one basin knowing that in the other basin the situation could be reverted. It is also notable the competitive but friendly spirit of the negotiations and the political willingness of Franklin D. Roosevelt and Manuel Avila Camacho administrations to show that during war times it was possible to establish agreement between nations (Enriquez-Coyro 1976). Finally, on February 3rd, 1944 was signed in Washington D.C. the treaty between Mexico and the United States that defines the rules for water allocation between both countries of the Colorado and Tijuana Rivers and of the Rio Grande (IBWC 1944).With the signature of the treaty the International Boundary and Water Commission (IBWC) was created, formed by two sections: the American and Mexican section. The IBWC replace the International Boundary Commission (IBC).

2.2.2.3 After Treaties era

In this section is analyzed the period after the signature of the 1944 Treaty; however, there is no "after treaties era" since the 1944 Treaty is a dynamic international agreement that is amended each time a minute is signed. Up to now, there are 318 minutes and the last minute was signed on December 2010. Besides, there are two more international agreements signed by the United States and Mexico after 1944, the Chamizal Convention of 1963 (IBWC 1963) and the Treaty of 1970 (IBWC 1970). These two treaties are more focused in the border line delineation and solution of conflicts because of the changing in the Rio Grande/Rio Bravo course.

For the Rio Grande/Rio Bravo, the 1944 Treaty established the delivery of water from Mexico to the United States of 1/3 of the flow reaching the Rio Grande/Rio Bravo from 6 Mexican tributaries (Conchos, Arroyo Las Vacas, San Diego, San Rodrigo, Escondido and Salado) provided that this third shall not be less, as an average amount in cycles of 5 consecutive years, than 431.721×10^6 m^3/year, although such one third may exceed this amount. Two international dams, Amistad and Falcon, were built to store water for both countries. Also, it was provided that the treaty cycles can expire earlier than five years, if the conservation capacity assigned to the U.S. in both international dams is filled with water belonging to the U.S.

The technical report presented by Orive-Alba (1945) to the Mexican Chamber of Senators shows the calculations used to define the U.S. and Mexican allotment in the Treaty, and the expected deliveries of water from Mexico to the U.S. Two different cases were considered by Orive-Alba to evaluate the treaty obligations. Case I only considers 5 years cycles, before the dam's construction, when the system is considered to not be fully developed. Historically, this case happened during the first 3 treaty cycles, from Oct/1953 to Sep/1958. Case II considers the system fully developed, after the international dams' construction. In this case, during wet years the treaty cycles can expire earlier if the conservation capacity assigned to the U.S. is filled. Historically, Case II happened since treaty cycle 4 up to the present (treaty cycle 31).

Three performance criteria are used to analyze the performance expected when the treaty was signed and what actually happened for the treaty deliveries from Mexico to the U.S.: *Reliability*, *Resilience* and *Vulnerability*. Reliability refers to the frequency in time an event is successful in relation to the total period of time analyzed. A successful event is defined as the event when there is no deficit in the delivery of treaty obligations. Resilience is the probability that once the system is in a deficit, the next period the system recover to a successful event. Vulnerability is the expected value of the deficits, in other words, it is the average of the deficits experienced. These performance criteria are discussed in detail in Chapter 3: Performance Criteria.

Table 2-1: Reliability, Resilience and Vulnerability of the Mexican delivery of water according to the 1944 Treaty.

	Chase I: System Undeveloped		Chase II: System Developed	
Performance Criteria	Expected (%)	Historical (%)	Expected (%)	Historical (%)
Reliability	56%	67%	42%	63%
Resilience	65%	100%	80%	67%
Vulnerability	10%	27%	9%	30%

For Case I (see Table 2-1), the reliability improved from an expected value of 56% to 67% that actually happened. This means that the system was in fewer times in deficit than what was expected, 11% of the time less. Also, the system recovered faster, the resilience increased from an expected value of 65% to an historic value of 100%. Historically, when the system failed the following cycle the deficit was paid off. On the contrary, the vulnerability got worse, from an expected value of 10% to an historic value of 27%. When a deficit in the treaty obligation happened, it was of 27% of the treaty obligations (2,159 million m^3/cycle) instead of 10%, as it was planned. The people involved in the treaty negotiations knew that the system will fail very frequently, in fact 44% of the time (1-Reliability) and that system does not recovered vary fast (65% of the times around two out of three times), but they relied that the failures will be small (10% of the treaty obligations) (Orive-Alba 1945). Historic data showed that the system does not fail as much as they thought, only 33% of the time, and the recovery is faster (100% of the times for Case I, from Oct/1953 to Sep/1968) but the deficits are much bigger of what they planned (about 3 times bigger, 27% of the treaty obligations).

For Case II (see Table 2-1), as the system is right now, the reliability improved from an expected value of 42% to an historic value of 63%. Historically, the system was less time in a deficit of what was expected. However, the system recovered slower and the deficits were bigger of what was expected. The quickness of recovery (Resilience) decreased from an expected value of 80% to an historic value of 67%; historically it was more difficult to recover from a deficit of what was expected. The severity of the deficits (Vulnerability) increased from an expected value of 9% to an historic value of 30%. When a deficit in the treaty obligation happened, it was of 30% of the treaty obligations (30% of 2,159 million m^3/cycle) instead of 9%, as it was planned. The people involved in the treaty negotiations knew that the system will fail very frequently, in fact 58% of the time! (Orive-Alba 1945, Enriquez-Coyro 1976). However, they relied that the failures will be small (9% of the treaty obligations), and the system will recover from deficit very frequently (80% of the times; around four out of five times). Historic data showed that the system does not fail as much as they thought, only 47% of the time (1-Reliability), but the recovery is slower (67% of the times, two out of thee) and the deficits are much bigger of what they planned (more than 3 times bigger, 30% of the treaty obligations). In conclusion, historical treaty deliveries have shown different performance than the 1944 Treaty signature premises: higher reliability, lower resilience and high vulnerability.

2.2.3 Challenges

2.2.3.1 Planning and management

Over allocation of water rights

In 2007 the Rio Grande/Rio Bravo was named one of the world's top ten endangered rivers by the World Wildlife Fund (WWF 2007) because of the mismatch between the water availability and water rights conferred in the basin. In Mexico, the over allocation of water rights was identified since late 1990's, when the federal government made a census to identify all the water users in the basin (SEMARNAT

1995, SEMARNAT 2002). Later, the minister of agriculture made public the PADUA program, with the objective to reduce the water rights conferred to irrigation districts in order to match the demand with the availability of water. This program is available for eleven irrigation districts from which six are located in the Rio Grande/Rio Bravo basin (SAGARPA 2003). Furthermore, in 2008 CONAGUA (water authority in Mexico) published the annual water availability study for the Rio Grande/ Rio Bravo (CONAGUA 2008.b). This study concluded there are more water rights than the actual natural availability of this resource.

In the United States, during the last drought (1994-2003) the water supply for the United States was compromised. At the beginning of the drought (1994-1996) the water supply for agriculture water users below Falcon was on average 78% (1400 million m^3/year) of their full allocation demand (1801 million m^3/year), for the rest of the drought (1997-2004) the water supply was on average 53% (950 million m^3/year) of the full allocation demand (IBWC 2009). This uncertainty in the water supply provoked the 75th Texas Legislature to order a study (Brandes 2004) that defined water availability, water use limits and vulnerabilities of the system (TWDB 2001). As a result, the “Current Allocation” for US water users other than municipal, domestic and industrial was set at 70% of the full allocation demand, acknowledging the over allocation of water rights (TCEQ 2007). The current allocation has been further reduced to 62% of the full allocation demand (personal communication, Carlos Rubenstein, Commissioner, TCEQ, October 2009).

Figure 2-4 *a* and *c* show the water consumption for Mexican water users along the Rio Grande/Rio Bravo mainstream and in the tributaries, respectively (CONAGUA 2008.b, Sandoval-Solis 2011). Both figures show a linear increase in the water consumption due to irrigation district expansion, mostly from 1965 to 1994, and after that, a dramatic decrease in their water supply during the 90's drought (1994-2007). Water consumption before the 90's drought was much higher than the annual average consumption (1950 to 2004) of water users along the Rio Grande/Rio Bravo and in Mexican tributaries, which are 1,576 and 2,392 million m^3, respectively.

Figure 2-4 *b* shows the water consumption for U.S. water users along the Rio Grande/Rio Bravo mainstream (IBWC 2009, Sandoval-Solis 2011). Water consumption for U.S. water users has been close to the mean annual value (1,442 million m^3) except for 1989 when more than 2,000 million m^3 were consumed. Notice that the mean annual water consumption for Mexican and U.S. water users along the Rio Grande/Rio Bravo mainstream is about the same, 1,576 and 1,442 million m^3 respectively. The main difference is that U.S. water consumption does not vary as much as in Mexico.

In the early 2000's, reduction in the irrigation districts' water rights was discussed by authorities from both countries (SAGARPA 2003, IBWC 2003, Brandes 2004); the drought of the 90's showed that the prior 1994 water consumption was unsustainable. U.S. and Mexican authorities recognized that it was physically impossible to continue providing the water consumption of the early 90's (1990-1994). In 2004, water rights in Mexico and the US were estimated to be 4,532 and 2,129 million m3/year, respectively (CONAGUA 2004, Brandes 2004). Recently, several policies have been implemented to reduce the water rights in the basin, such as buy-back of water rights (Chapter 6.2.1), infrastructure improvements (Chapter 6.2.3) and water rights reduction (Chapter 6.3.1). In 2008, water rights in Mexico and the US have been reduced to 4,401 and 1,953 million m^3/year, respectively. These values are still above the historic mean annual water consumption for Mexico and the U.S., which are 3,968 and 1,442 million m^3, respectively (Sandoval-Solis 2011). Furthermore, the previous analysis does not consider water for the environment; these values shows the problem of over-allocation of water rights in the basin.

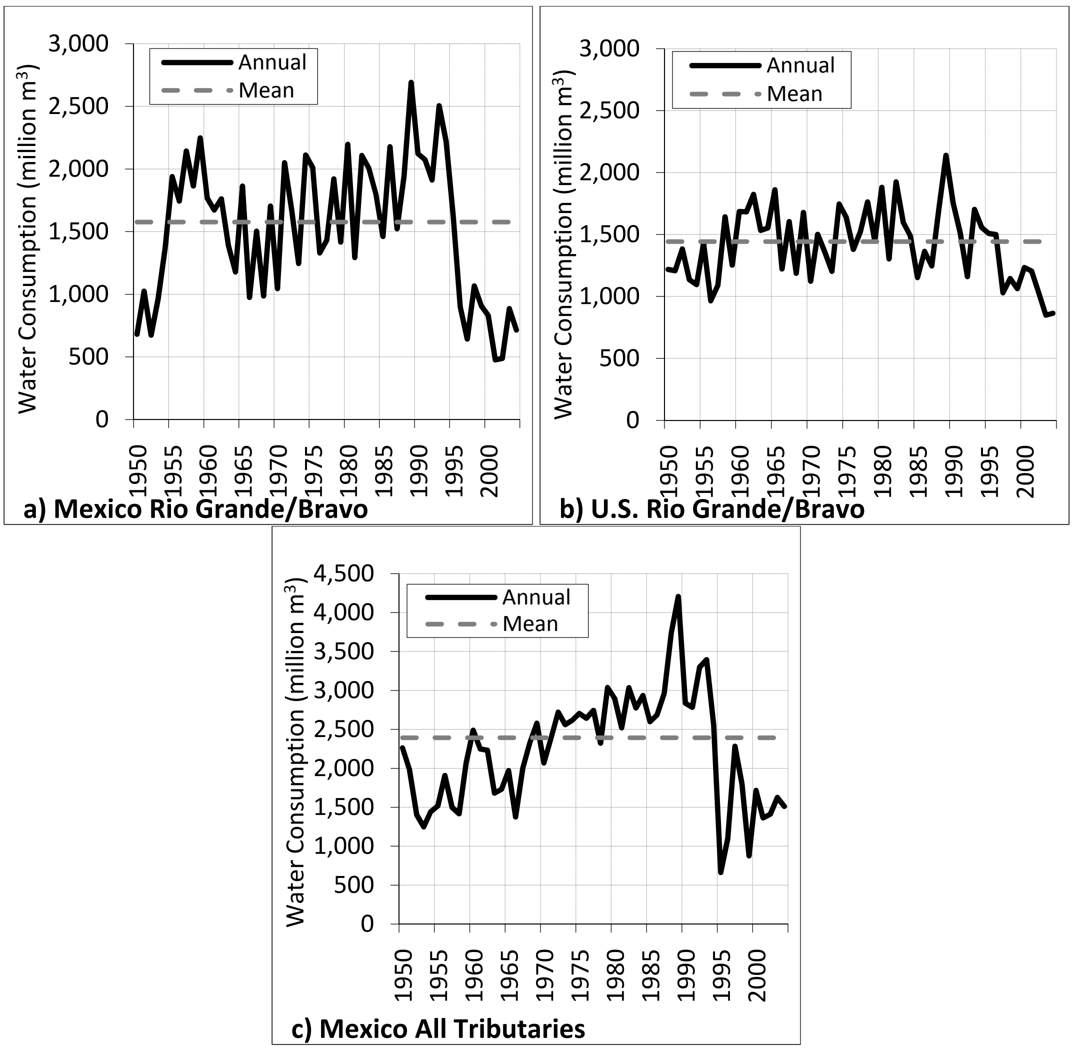


Figure 2-4: Water consumption in Mexico and the U.S. along the Rio Grande/Rio Bravo and in Mexican tributaries.

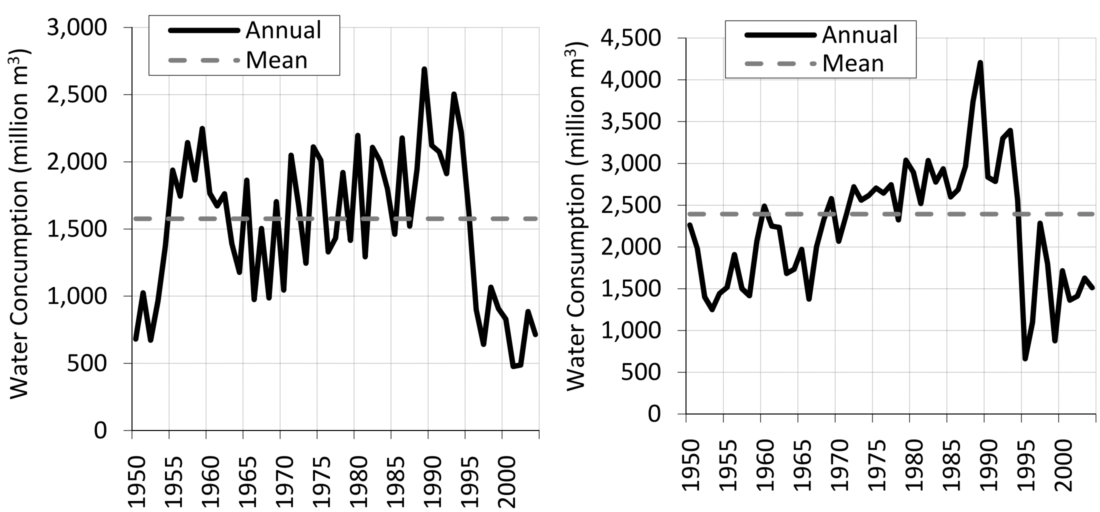
Low efficiency in the system

In the basin, agriculture accounts for 84% of the total water demand; water in the basin is mainly used for irrigation. In Mexico, conveyance and applications efficiencies for agriculture are usually low (Collado 2002); for instance, prior 2003 the global efficiency in irrigation district 005 Delicias was estimated of 33%, meaning that only 33% of the water diverted from the reservoir will actually be consumed by the crop (IBWC 2003). That year was implemented an agreement through Minute 309 to improve the infrastructure in irrigation districts 005 Delicias, 090 Bajo Rio Conchos and 103 Rio Florido to increase their global efficiency from 33%, 35% and 33% to 55%, 47% and 48%, respectively (IBWC 2003). The prior improvement efficiencies (<35%) can give us an idea what are the efficiencies in other irrigation districts without infrastructure improvements. Unfortunately, improvement infrastructure programs, such as Minute 309, have not been implemented in other irrigation districts.

In the lower Rio Grande valley and Maverick county, prior to 2000 conveyance efficiencies by irrigations Districts range from 40% to 95% (Fipps 2000), with an average conveyance efficiency of 71%. On farm efficiencies vary from 30% to 80%; these values are uncertain given the lack of data and collaboration from irrigation districts in this area (Fipps and Pope 2004). Considering the previous uncertainty, global efficiency can vary from 21% to 76%. From 2002 to 2004, several water conservation projects were implemented in the lower Rio Grande Valley (Hidalgo and Cameron counties), and Maverick county to improve the conveyance efficiencies in irrigation districts (NADB 2010.a and 2010.b); although, water savings from these project has not been published.

Undefined Water Regulation

Historically, water supply in the basin has varied significantly, showing inconsistency in water management of the basin. For Mexico, Figure 2-5 shows the historic water consumption from 1950 to 2004 along the Rio Grande/Rio Bravo and in the Mexican tributaries (CONAGUA 2008.b). This figures show how variable has been the water supply for Mexican water users; while municipal and domestic users have secured their water supply, irrigation districts have experienced uncertainty in their water allocation. In 2002 there was an unsuccessful initiative to implement a regulation in the basin (Collado 2002); up to now, there is no specific regulation to allocate water for irrigation districts that accounts for 84% of the water rights. Similarly, there is no policy to deliver treaty obligations from Mexico to the U.S. according to the 1944 treaty.



a) Along the Rio Grande/Rio Bravo **b) All Tributaries**

Figure 2-5: Water Consumption for Mexico 1950-2004

In the U.S, regulations are already defined to allocate water in the Rio Grande/Rio Bravo basin (TCEQ 1938 and 2006); however, water supply has varied along the time (see Figure 2-6) (IBWC 2009). During the 1944 treaty signature, the consumptive use of water along the Rio Grande/Rio Bravo mainstream was estimated 1,949 million m^3/year (Sandoval-Solis and McKinney 2011). During the drought of the 50's (1948-1957), water supply was reduced to 1,190 million m^3 on average per year, 66% of their full allocation water right (1,802 million m^3/year). In the following three decades (60's to 80's), water supply used to be around the mean, 1442 million m^3/year, 80% of the full allocation right. Because of the drought of the 90's (1994-2007), water supply for agriculture and mining water use in the thirteen Water Master Sections have been reduced progressively; for instance, in 2004 water rights were reduced to 70% of their full allocation (Brandes 2004) and recently, in 2009, this value has been reduced to 62% (personal communication, Carlos Rubenstein, Commissioner, TCEQ, October 2009).

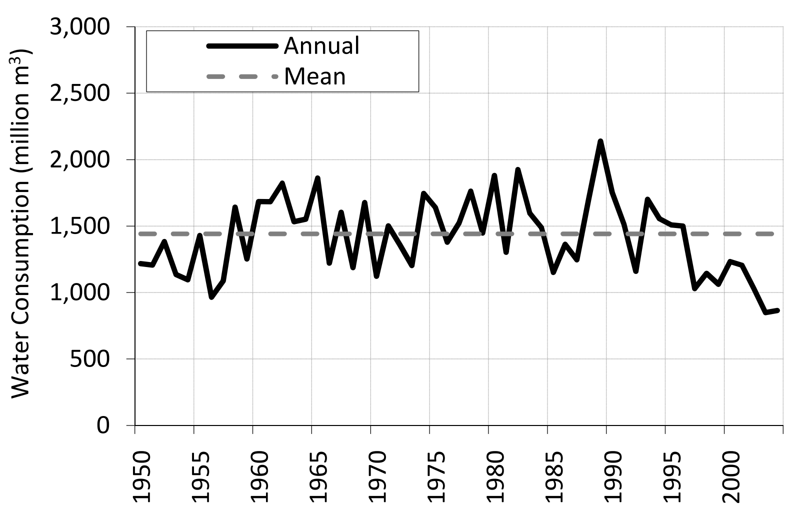


Figure 2-6: Water Consumption for the U.S., 1950-2004

2.2.3.2 Water Quality

Besides water quantity, there are issues regarding water quality in the Rio Grande/Rio Bravo basin. To assess this problem, the TCEQ has divided the basin in three regions: upper basin, from El Paso/Cd. Juarez to Amistad Reservoir; middle basin, from Amistad to Falcon; and the lower basin, from Falcon to the Gulf of Mexico. Primary water quality concerns include: a) high bacteria levels in all regions, it is suspected that communities are discharging their wastewater into the mainstream without any treatment; b) high salinity levels (chloride, sulfate and TDS) in the upper region, this can be caused due to returns of irrigation districts, invasive species, scarcity of water, among others problems; c) high nutrients level (ammonia and phosphorus) in all regions, because of municipal discharged without any treatment; and d) excessive growth of aquatic weeds in the lower basin (IBWC 2008, Ingol-Blanco and McKinney 2009). Besides, toxicity studies along the border have found high levels of toxics in water (PCB's, Cyanide, mercury and residual chlorine), sediment and fish (TCEQ 1995). Despite all of this, the situation has improved in recent years because of the investment in wastewater and water systems (Texas Environmental Profiles 2004, NADB 2010.a and 2010.b); bi-national cooperation, such as the Border 2012 project have provided guidance and financial resources to attend public health and water quality problems along the border (EPA-SEMARNAT 2009), but water quality is still an issue to improve in the basin (IBWC 2008).

2.2.3.3 Environment

In addition to the problems of water quantity and quality, environmental problems are also present in the Rio Grande/Rio Bravo Basin. Prior the dam's construction, the Rio Grande/Rio Bravo was constituted by two hydrological regimes: (1) in the northern branch, above Ojinaga/Presidio, the flood regime was snowmelt driven from the Rocky

Mountains, with a peak flow in late spring, meanwhile (2) in the southern branch, below Ojinaga/Presidio, the flood regime was driven by summer-autumn rainfall, mostly water coming from the Rio Conchos whose headwaters are in the Sierra Madre Occidental (Schmidt et al. 2003). Even though the drainage area of the northern branch is bigger than the Rio Conchos sub-basin, the flow provided by the Rio Conchos was much larger than the northern branch flow. The alteration of the natural regime has threatened the environmental health of aquatic and riparian ecosystems.

Reservoir alteration

Reservoir construction in the basin degraded the environmental conditions in the basin. Figure 2-7 and Figure 2-8 shows the reservoir construction for the United States and Mexico, respectively. There is evidence that in the Big Bend reach before the mid 1940's, the Rio Grande/Rio Bravo mainstream preserved a wide, sandy and multi-threaded river. However, after the mid 1940's, a progressive channel narrowing has been the constant in this reach, temporally interrupted by occasional large floods that widen the channel and channel narrowing resumed again (Dean and Schmidt 2011). Narrowing has occurred by the vertical accretion of fine-grained deposit on top of sand and gravel bars. Sand and gravel bars that used to be part of the dynamic channel were progressively invaded by vegetation. The invasion of non native species, such as salt cedar (*Tamarisk* spp.) since 1910's or giant cane (*Arundo donax)* since 1938 (Everitt 1998), has exacerbated the process of channel narrowing and vertical accretion. The geomorphic nature of the Rio Grande/Rio Bravo has changed from a wide, laterally unstable, multi-thread river before mid 1940s; to a stable, single-thread channel with cohesive, vertical blanks, and few active in channel bars after 1940 (Dean and Schmidt 2011). This shift in the geomorphic conditions was caused primarily by dams' construction, mostly since 1915, and it has been exacerbated by the invasion of non-native species after late 1930's.

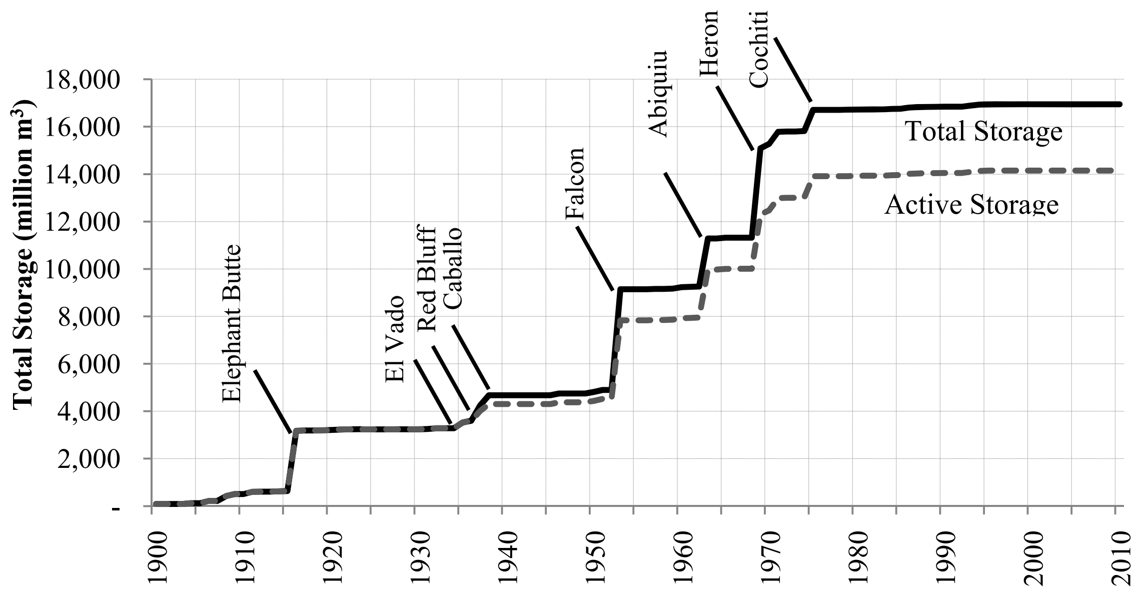


Figure 2-7: Reservoir development in the United States for the Rio Grande/Rio Bravo

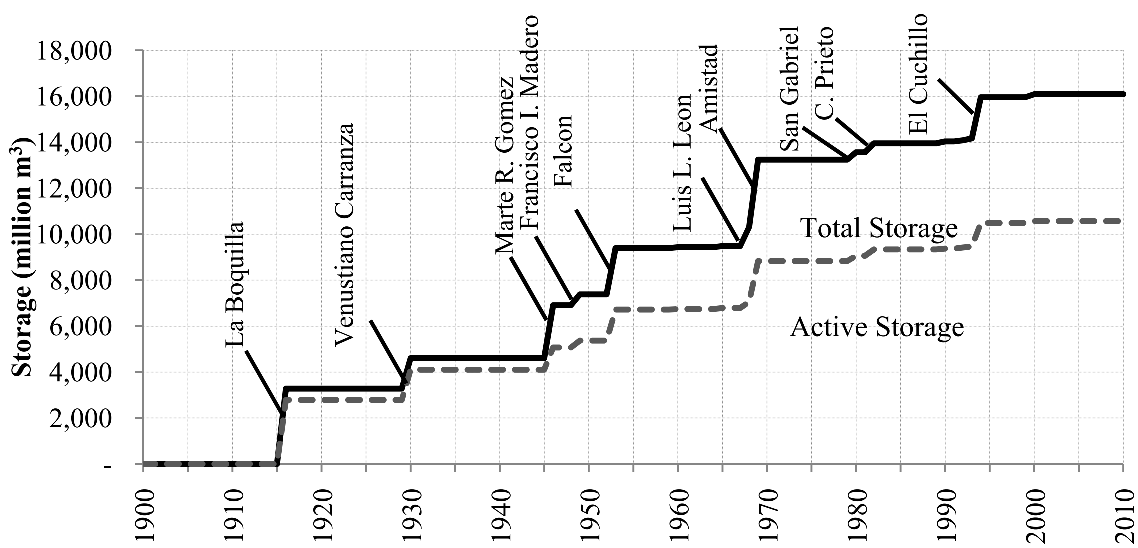


Figure 2-8: Reservoir development in Mexico for the Rio Grande/Rio Bravo

Another point of environmental concern is the outlet of the river at the Gulf of Mexico. In February of 2001 the river mouth was blocked by a sand bar caused by low flow conditions due to the 90's drought, upstream diversion and invasive aquatic vegetation (Mathis et al. 2006, Blankinship 2005); it remained closed until September 2001 when the IBWC dredged it open (IBWC 2002). Subsequent tidal water changes again closed the mouth until November 2002, when higher tides and increased rainfall runoff partially opened it. The scarcity of flow in this reach is a threat to the estuary's sustainability; side effects include degradation of the environment, lost of species and saline intrusion in aquifers, among others.

Ecosystems

The Rio Grande/Rio Bravo Basin is one of the most biologically-diverse regions in North America, possessing a range of important aquatic and terrestrial ecosystems (WWF 2007). It traverses three major ecological regions (Southern Rocky Mountains; Chihuahua Desert; Tamaulipas Thorn Scrub) exhibiting a mosaic of mountain, desert and coastal habitats. The lower Rio Bravo valley provides habitat for millions of migratory birds to feed and rest during migration, it is a major bird watching site in North America (WBC 2011). Reptiles and amphibians thrive in wetlands through the basin, including many sea turtles, lizards, snakes, frogs and salamanders.

Degradation of river water quality and riparian vegetation has changed significantly over time. Some of the threatened or endangered species include: the bald eagle (Haliaeetus leucocephalus), Gulf Coast jaguarundi (Herpailurus yagouaroundi cacomitli), star cactus (Astrophytum asterias), Mexican long-nosed bat (Leptonycteris nivalis), Rio Grande silvery minnow (Hybognathus amarus), Walker's manioc (Manihot walkerae), and black-footed ferret (Mustela nigripes) (USC 1973). Causative factors include construction of dams, variable water flow rates, urbanization, ecosystem fragmentation, and introduction of non-native species. Hydrologic modifications and exotic species have worsened the conditions for native species. Few undisturbed, natural communities remain in the lower portion of the basin. The final 48 km of the Rio Bravo is a tidal river system, with the offshore portion of the Gulf of Mexico directly influenced by the river's freshwater discharge plume comprising the Rio Grande/Rio Bravo estuary system.

Undefined Environmental Water Rights

Despite the fact that regulations on both countries considered the environmental protection of ecosystems (USC 1973 and CONAGUA 2008.a), there is no water management policy in place that delivers water for environmental purposes. Historically, this basin has been manipulated in an exclusive human water resource management (Enriquez-Coyro, 1976), not considering the environmental needs for the native ecosystems. The Convention of 1906 (IBWC 1906), the Rio Grande Compact (TCEQ 1939) and the Treaty of 1944 (IBWC 1944) prove the fact that the water in this basin was thought to be used exclusively for human benefit. The water allocation in these agreements obeys exclusively the human concerns, leaving out the natural water requirements of the basin. In fact, article 3 of the treaty of 1944 does not mention the "Environment" as beneficial use of water (IBWC 1944).

In addition, there is a lack of environmental flow estimation along the basin; while some regulations provide the legal framework to protect the environment (CONAGUA 2008.a, LST 2007); these regulations cannot be enforced due to the absence of environmental flows estimation along the rivers. In recent years, there has been certain progress regarding this topic; in 2006 the World Wildlife Fund estimated the environmental flows in 9 locations along the Rio Conchos basin through the use of the Building Block Method (WWF 2006). The geomorphology, flora and fauna (fish and invertebrates) were considered to determine the maintenance and drought flows necessary to meet the environmental requirements. Besides, a first draft of environmental flows have been determined for the Big Bend reach, along the Rio Grande/Rio Bravo mainstream, this estimation was obtained through a historic hydrologic analysis (Sandoval-Solis et al. 2010).

Invasive species

In addition to the previous problems, at least three invasive species are proliferating in the Rio Grande/Rio Bravo basin: 1) Russian Olive (*Eleagnus angustifolia*) in the upper basin, above Elephant Butte reservoir, 2) salt cedar or Tamarisk (*Tamarix spp*) and 3) giant cane (*Arundo donax*), both of them in the middle basin, from El Paso/Ciudad Juarez Valley to Amistad reservoir (Everitt 1998, Dudley et al. 2000, Schmidt et al. 2003). Salt cedar is a highly drought resilient species that consumes important amounts of water and increases the salinity of soil, it is a paramount opportunistic species that spreads and reproduce very efficiently occupying the space and resources of native species.

There have been several efforts to eradicate invasive species from the basin, the Big Bend National Park Service have physically removed plants, use herbicides, introduced tamarisk beetles (*Diorhabda carinulata*) and evaluated the eradication of no-native species by floods. Preliminary results of eradication efforts have shown that flooding mitigates the impact of Tamarisk on soil salt loading (Cederborg et al. 2008). In 2008, most of the tamarisk located along the river in the Big Bend reach was removed by the floods of that year. This pest control policy is very unlikely, the construction of large reservoirs in the basin has decreased the occurrence of these events, collaborating in the proliferation of tamarisk. Besides this is an undesired policy by people living close the river.

2.2.4 Current Status

Regarding the water management in the basin, after the publication of the water availability for Mexican water users by CONAGUA (2008.b), the Rio Bravo basin council has started a process of negotiation were it will be defined the regulation to allocate water for municipalities and irrigation districts in the basin (Arreguin 2010), these water rights account for 99% of the total Mexican water rights. In order to build trust among the parties, the basin council is building a water planning model where policies will be tested. This planning model will be built using the algorithms and allocation policies of the Rio Grande/Rio Bravo WEAP model built in the present research; besides several policies proposed in the present research will be considered by the Mexican basin council. In 2010, regional water plans for regions E, J, and M have been published by the TWDB (2010.a, b and c). These documents describe several water management policies that will be implemented to deal with the increase of population and energy requirement, such as: water conservation measures in municipalities and irrigation, reuse of water either from municipal or agriculture drains, groundwater development, brackish and seawater desalination, acquisition of additional water rights. Out of the previous policies, four policies account for 75% of the water savings planned: 1) increase in efficiency of on-farm water application, 2) water conservation in conveyance for irrigation, 3) acquisition of water rights through purchase and 4) brackish desalination.

Regarding treaty obligations, cycle 31 is the current treaty cycle, it started on October 26th 2010. Cycle 30 was closed on October 25th 2010, it lasted about one year and a half, and it was closed because of the filling of the US storage capacity at both international reservoirs. Up to February 2011, the storage for the US and Mexico at the international reservoirs are 97% and 90% of their conservation capacity respectively;

2008, 2009 and 2010 have been wet years (IBWC 2011). Reservoirs in Mexico are above 90% of their conservation capacity; main reservoirs in Rio Conchos, Salado and San Juan are above 94% of their conservation capacity (CILA 2011). In the US, Elephant Butte and Caballo reservoirs are at their 24% and 11% conservation capacity, respectively (IBWC 2011).

Regarding the environment, in 2006 the environmental flows for nine control points in the Conchos basin were estimated by the World Wildlife Fund (Chapter 6.2.5); these flows are used to evaluate the environmental requirements for the basin. More recently, in 2010 the author proposed an annual hydrograph for environmental restoration flows at the Big Bend Reach (Sandoval-Solis et al. 2010), this hydrograph is based on the hydrologic characteristics prior 1946, when the Rio Grande/Rio Bravo maintained a wide, sandy, multi-thread channel (Dean and Schmidt 2011). This investigation is currently undergoing and not included in the present document; at this moment, the author is investigating how to operate the infrastructure in order to obtain environmental flows for this region without harming water users, the treaty obligations or increasing the flooding risk at Presidio/Ojinaga. In Texas, Senate Bill 3 provides the legal framework to determine and promote environmental flows for the state (LST 2007). In March 2011, the Science Advisory Committee will be formed; they will provide an objective perspective, evaluation and estimation of environmental flows in the Rio Grande/Rio Bravo stream to the Advisory Group, which is integrated by members of the senate, House of Representatives and people appointed by the Governor. In the lower Rio Grande valley, the World Birding Center (WBC) was created as a network of sites for bird watching; along their 9 locations it is possible to appreciate the ecological treasures of the lower Rio Grande valley. The objective of the WBC is to protect native habitat and ecosystems while increasing the understanding and appreciation of birds and wildlife (WBC 2011).

Regarding water quality, the IBWC Texas Clean River Program has conducted several monitoring campaigns along the Rio Grande/Rio Bravo mainstream. The analysis of these data has shown problems of bacteria, high salinity, nutrients, and excessive growth of aquatic weeds in the lower Rio Grande basin (IBWC 2008). In 2010, two were the main concerns downstream Falcon to the Gulf of Mexico: 1) bacteria, listed as the main concern and 2) mercury, dissolved oxygen and nutrients. The proposed work plan of the Clean River Program for 2010-2011 includes water quality data monitoring in 46 stations, data analysis and reporting, stakeholder participation and outreach. In March 2011, the IBWC is organizing a summit about water quality and sanitation along the border. In this summit will be addressed the current problematic and possible solutions to water quality, sanitation, financing along the US-Mexico border.

Regarding politics between Mexico and the U.S., during the drought of the 90's (1994-2007), relations between both countries were tense because of the increase in water debt of Mexico. Presidents George W. Bush and Vicente Fox organized meetings to discern solutions about the problematic of water scarcity, Mexico's water debt and how it will be paid; Minutes 307, 308 and 309 are the agreements of these presidential meetings (IBWC 2001, 2002 and 2003). In the Colorado River, since 1988, lining the All American Canal (AAC) started sounding as an option to save water for California; in 2002-2003 this project gained momentum and the final design for the AAC was authorized by the California legislature in September 2003 (USBR 2006). Savings of the lining of the ACC were estimated of 67,700 acre-foot/year (83.5 million m3/year). The groundwater hydrology in this region conveyed the infiltration losses of the AAC to Mexican territory, Mexican farmers and the Colorado Delta habitat were benefited from these losses. Because of the Mexican water debt in the Rio Grande/Rio Bravo, Mexican authorities in the Colorado delta did not raise any claim about the drawbacks that the lining of the AAC would provoke to farmers and the environment (Personal communication, Carlos A. de la Parra, El Colegio de la Frontera, 2010); they did not have a strong argument for claiming harm considering that farmers in Texas were affected by the unmet of Treaty obligations from Mexico. Once again, problems in one basin, the Rio Grande/Rio Bravo, affected the management on the other basin, the Colorado River. When the Mexican water debt was paid in 2007 (IBWC 2007), Mexico started claiming affectations because of the lining of the ACC but it was too late, the project already started in June 2007 (USBR 2010) and despite the fact of the NGOs suited the State of California, in 2010 the lining of the canal was completed (USBR 2010).

In Mexico, politics have been related to downstream – upstream water users, the state of Tamaulipas (downstream) against Chihuahua (upstream) state and federal versus regional water management. In 1994 was founded the *Rio Bravo Basin Council*, an organisms whose objective is to determine efficient policies to allocate water in the Rio Bravo (CTMMA 2001). This public organism is in charge of the decision making process for the water planning and management of the basin. The *Basin Council* is integrated by representatives of: a) each basin's state, b) water users and c) federal government (CONAGUA 2008.a). The basin council is in charge of defining rules (regulations) for water allocation in the basin, in Mexican territory. In 2008, the water availability study was published as an agreement of the basin council (CONAGUA 2008.b); this is the first step to define a regulation for water allocation in the basin. At this moment, the basin council is calculating the naturalized flows for the Rio Grande/Rio Bravo basin in Mexican territory. The politics of the basin (discussions, decisions, and agreements) are expressed on this council; this is the place where upstream (Chihuahua) and downstream (Tamaulipas) users defend their positions and negotiate about water allocation, rules and action that will benefit their interest. Results of this research have been presented to the basin council.

Chapter 3 Methodology

In this chapter is defined the methodology used to evaluate water management policies in large scale basins. The first section presents the performance criteria used to evaluate essential or desired characteristics required in the water management for water users, the environment or system requirements. The second section explains the summarization of performance criteria results by using the *Sustainability Index* and the *Relative Sustainability*. This section explains the properties and improvements proposed for the Sustainability Index as well as its calculation procedure. Also in this section is introduced the Relative Sustainability, which is an index that summarizes the results of Sustainability Indices. The Relative Sustainability is useful to show results for water users' groups. The third section describes the integration of results.

3.1 Performance Criteria

Performance criteria are used to evaluate and compare the performance of water management policies. They evaluate essential or desired characteristics required in the water management for water users, the environment or system requirements; and make possible their comparison with alternative policies.

Performance criteria using central measures of location have been used to evaluate water resources systems. Examples of these performance criteria are, among others, average: storage, water supply, evaporation, treaty delivery, municipal shortfalls (deficits), and outflow of water from a system (Vigerstol 2002). Probability based performance criteria include time-based (annual, monthly) and volumetric reliability (TCEQ 2007), resilience (Hashimoto *et al*. 1982).

For each water user, environmental and system requirements, five performance criteria are calculated:

1. *Reliability* –accounts for the period of time the water demand is fully supplied;
2. *Resilience* – accounts for the policy's adaptability to hydrologic changing conditions;
3. *Vulnerability* – account for the expected severity of the deficits;
4. *Maximum Deficit* – account for the worst deficit case; and
5. *Standard Deviation* – accounts for the variability in the water supply.

3.1.1 Reliability

Reliability is the probability that a water demand is fully supplied during the period of simulation (Klemes *et al*. 1981; Hashimoto *et al*. 1982). The time based reliability (McMahon *et al*. 2006) is considered; which is the portion of time that water demand is fully supplied. We define a deficit as (Loucks 1997):

$$D_t^i = \begin{cases} X_{Target,t}^i - X_{Supplied,t}^i & if\ X_{Target,t}^i > X_{Supplied,t}^i \\ 0 & if\ X_{Target}^i = X_{Supplied,t}^i \end{cases} \qquad \text{Equation 3-1}$$

where: $X^i_{Target,t}$ is the water demand for the i^{th} water user, and $X^i_{Supplied,t}$ is the water supplied in the t^{th} time period. Finally, the reliability for the i^{th} user is:

$$Rel^i = \frac{\#\ of\ times\ D_t^i = 0}{n} \qquad \text{Equation 3-2}$$

where n is number of time intervals considered, often used the total number of years or months, depending on the water management unit of time.

3.1.2 Resilience

Resilience is the system's capacity to adapt to changing conditions. Since climate conditions are no longer steady, resilience must be considered as a statistic that assesses the flexibility of water management policies to adapt to changing conditions (WHO 2009; IPCC 2007.b). The classic definition of resilience is the probability that a system recovers from a period of failure, e.g., a deficit in water supply (Matalas and Fiering 1977; Hashimoto *et al*. 1982). Moy *et al*. (1986) used the maximum number of consecutives deficit periods prior to recovery as an alternative definition of resilience. According to Hashimoto *et al*. (1982), resilience is the probability that a year of no-deficit follows a year of deficit in the water supply for the i^{th} water user. This is a useful statistic to assess the recovery of the system once it has failed. Resilience is expressed as:

$$Res^i = \frac{\#\ of\ times\ D_t^i{=}0\ follows\ D_t^i{>}0}{\#\ of\ times\ D_t^i{>}0\ ocurred} \qquad \text{Equation 3-3}$$

3.1.3 Vulnerability

Vulnerability is the likely value of deficits, if they occur (Hashimoto *et al*. 1982). Essentially, vulnerability expresses the severity of failures. Vulnerability can be expressed as: (1) the average failure (Loucks and van Beek 2005); (2) the maximum of the average shortfalls over all continuous failure periods (Hashimoto *et al*. 1982; McMahon *et al.* 2006); and (3) the probability of exceedance over a certain deficit threshold (Mendoza et al. 1997). The first approach is used, the expected value of deficits. Dimensionless vulnerability is defined by dividing the average annual deficit by the annual water demand for the i^{th} water user:

$$Vul^i = \frac{\left(\frac{\sum_{D_t^i>0} D_t^i}{\#\ of\ times\ D_t^i>0\ occured}\right)}{Water\ Demand^i} \qquad \text{Equation 3-4}$$

3.1.4 Maximum Deficit

The maximum deficit, if they occur, is the worst-case deficit for the i^{th} water user

$$MaxDef'^{\,i} = \max(D_t^i) \qquad \text{Equation 3-5}$$

A dimensionless maximum deficit is used by dividing the volumetric maximum deficit by the annual water demand for the i^{th} water user

$$MaxDef^{\,i} = \frac{MaxDeficit'^{\,i}}{X_{Target}^{i}} \qquad \text{Equation 3-6}$$

3.1.5 Standard Deviation

The variance of the water supply for the i^{th} water user is:

$$(\sigma')^i = \sum_{t=1}^{n} \frac{\left(X_{Supplied,t}^{i} - \bar{X}_{Supplied}^{i}\right)^2}{(n-1)} \qquad \text{Equation 3-7}$$

Where:

$$\bar{X}_{Supplied}^{i} = \frac{1}{n}\sum_{t=1}^{n} X_{Supplied,t}^{i} \qquad \text{Equation 3-8}$$

Thus the standard deviation of the water supplied for the i^{th} water user in period t is:

$$\sigma'^{\,i} = \sqrt{(\sigma'^2)^i} \qquad \text{Equation 3-9}$$

This performance criterion indicates the variability of the water supply when part or all of a user's water demand is not supplied from controlled facilities, such as, unregulated rivers. A dimensionless standard deviation can be defined by dividing the volumetric standard deviation (7) by the water demand

$$\sigma^i = \frac{\sigma'^i}{X^i_{Target}} \qquad \text{Equation 3-10}$$

As shown in Eq. 3-10, the standard deviation (σ'^i) is scaled (standardized) dividing it by the water demand (X^i_{Target}), therefore the standard deviation is expressed as a percentage of the water demand. The purpose of this standardization is to obtain a criterion that varies from zero to one; this is a requirement for any criterion that is included in the Sustainability Index (explained in the following section). For the particular case of the Rio Grande/Rio Bravo basin, the water demand (X^i_{Target}) scales the Standard Deviation criterion (σ^i), providing a range of values from zero to one. When using any statistical criterion, such as: Vulnerability, Maximum Deficit, Standard Deviation, or Volumetric Reliability (McMahon et al. 2006), it must be guaranteed that the standardization value provides a criterion varying from zero to one.

3.2 Sustainability Index

Indices represent aggregate measures of a combination of complex development phenomena (Booysen 2002), or in other words, "synthesis of numerous factors into one given factor" (Sainz 1989). Several indexes have been developed for environmental processes such as the Environmental Index (Howmiller and Scott 1977; Milbrink 1983), Environmental Sustainability Index (Esty *et al*. 2005), the Multi-attributed Environmental Index (Hajkowicz 2005); and also some indices specifically for water resources, such as the Drought Risk Index (Zongxue *et al*. 1998), the Palmer Drought Severity Index (Palmer 1965), Fairness (Lence *et al*. 1977), Reversibility (Fanai and Burn 1997) and Consensus (Simonovic 1998).

In order to quantify the sustainability of water resources systems, Loucks (1997) proposed the Sustainability Index, with the objective to facilitate the evaluation and comparison of water management policies. The Sustainability Index is a summary index that measures the sustainability of water resources systems; it can be used to estimate the sustainability for water users and to obtain the relative sustainability by comparing the sustainability index among several water policies proposed. Frequently, indices are criticized because they are seen as a combination of disparate items (Hopkins 1991). The Sustainability Index summarizes essential performance parameters of water management in a meaningful manner, rather than adding factors of broad, sometimes unrelated, and distant categories.

3.2.1 By User

Loucks (1997) proposed the following sustainability index for the i^{th} water user

$$Sust^{i} = Rel^{\mathrm{i}} * Res^{\mathrm{i}} * (1 - Vul^{\mathrm{i}}) \qquad \text{Equation 3-11}$$

This sustainability index has the properties of: (1) its values varies from 0 to 1, or as a percentage from 0 to 100%; (2) if one of the three performance criteria is zero, the sustainability will be zero also; and (3) there is an implicit weighting, the index gives added weight to the criteria having the worst performance. The multiplicative computation of the sustainability index, rather than the additive form, considers each criterion as essential and non-substitutable. Sagar and Najanm (1998) suggested this as the proper manner for integrating performance criteria. The sustainability index is a meaningful mathematical approach to estimating the sustainability for a water user.

A variation of Loucks' sustainability index is proposed in this research, with the index defined as a geometric mean of M performance criteria (C^i_m) for the i^{th} water user

$$Sust^i = \left[\prod_{m=1}^{M} C^i_m\right]^{1/M} \qquad \text{Equation 3-12}$$

For instance, if three performance criteria (M=3) are selected: $C^i_1 = Rel^i$, $C^i_2 = Res^i$, and $C^i_3 = 1\text{-}Vul^i$; the sustainability index for the i^{th} water user is

$$Sust^i = \left[Rel^i * Res^i * \left(1 - Vul^i\right)\right]^{1/3} \qquad \text{Equation 3-13}$$

This sustainability index satisfies the properties of the sustainability index defined by Loucks (1997), but, in addition, has the following improvements:

Content – Allows the inclusion of other criteria of interest according to the necessities of each case. The sustainability index is not longer a fixed performance criteria related to water quantity; performance criteria of water quality and environmental performance might be included in the sustainability index. For instance, if the Total Dissolved Solids (TDS) of the water delivered to a user must be below a permitted value, the reliability for TDS not exceeding the desired threshold can be calculated and included in the sustainability index. Notice that the criteria (C^i_m) included in Equation 3-12 must have a scale from 0 to 1 and the desired criteria values tend to 1. Scaling and complements $1\text{-}C^i_m$ can be applied prior to including any performance criteria into Equation 3-12.

Clarity – the use of the geometric average scales the values of the sustainability index, generating numbers that are more practical to interpret and communicate. Suppose that a certain water user has a reliability, resilience and vulnerability of 50% for each performance criteria. The sustainability index calculated with the prior definition (Equation 3-11) and the proposed index (Equation 3-12) are 13% and 50%, respectively. The latter is more like an arithmetic average which may be viewed as being more realistic or intuitive than the former index that leads to a 13%, rather than a 50% value. The scaling of the sustainability index does not obscure poor performance; its only purpose is to scale the values and make the index more practical. Suppose the reliability for the water user increases from 50% to 60%; the original and proposed sustainability index values are 15% and 53%, respectively. Once again, the proposed index is easier to explain and is more encouraging. In addition, more than 3 parameters can be included in the sustainability index, the product of several factors will result in small numbers and without scaling, changes in the sustainability index might be difficult to discern.

***Flexibility* –** Several structures for the sustainability index might be applied in the same basin for different water users or types of use. For instance, sustainability indices for municipal or recreational water use may be integrated with different performance criteria than an index for agriculture water use. Water quality and environmental performance criteria may be included for municipal and recreational water use, respectively, while the standard sustainability index (Equation 3-13) might be appropriate for agriculture use. Sustainability does not mean the same thing for all water users and the proposed index allows it to be adjusted to suit the user or use of water.

The improvements to the sustainability index are meaningful and not merely mathematical. The updated sustainability index is a holistic approach to define the sustainability for each water user. The structure of the index incorporates tailor-made parameters that for some water users may be crucial in their water management; the scaling of the index allows a better display of the results; and the flexibility to use different index structures in the same system allows the meaningful discrimination of performance parameters for specific water users. The *Sustainability Index* should be seen as a *Water Resources Integrated Index* that summarizes the results of essential or desired performance criteria for water users, system and environmental requirements.

Other mathematic structures have been evaluated during the present research, such as arithmetic and harmonic average; in all these different structures tested, the relative change of the Sustainability Index is preserved when comparing to the reference scenario. Thus, the importance of the Sustainability Index is its relative change with respect to a defined reference scenario, which for the Rio Grande/Rio Bravo Basin is the Baseline Scenario (Chapter 6.1). The advantages of the Sustainability Index proposed in Equation 3-12 is that makes easier to identify if the water supply for as determined water users is unsustainable because its value is zero or tend to zero. This characteristic of the Sustainability Index implies that each performance criteria is considered an essential or desired characteristic of the water management for that particular user.

3.2.2 By Group

In order to compare groups of water users, the relative sustainability (Loucks 1997) was defined as a weighted average of sustainability indices; expressed as

$$Rel\ Sust^{k} = \sum_{i=1 \in k}^{i=j \in k} W^{i} * Sust^{i} \qquad \text{Equation 3-14}$$

Where W^i is a relative weight for the i^{th} water user, ranging from 0 to 1 and summing to 1. The relative sustainability is used to calculate the sustainability index for a group k that contains water users from i to j. If the sustainability of each user is weighted by its annual water demand, the sustainability index for the k^{th} group is expressed as

$$Rel\ Sust^k = \sum_{i=1\in k}^{i=j\in k} \frac{Water\ Demand^i}{Water\ Demand^k} * Sust^i \qquad \text{Equation 3-15}$$

where:

$$Water\ Demand^k = \sum_{i=1\in k}^{i=j\in k} Water\ Demand^i \qquad \text{Equation 3-16}$$

For the Rio Grande/Rio Bravo basin, annual water demands are used to calculate the weights in the relative sustainability (Eq. 3-15). The relative importance of each variable is reflected in the weights (Drewnowski 1974). One option is not to include explicit weights by doing an arithmetic average, also called an equal-attribute-based weighting system (Slottje 1991). Another option is to use explicit weights which can be obtained through: (a) a formal analysis such as utility theory analysis (Loucks *et al*. 1997; Von Neumann and Morgenstern 1974), the method of principal components analysis or by a hedonic model weighting the attributes according to regression coefficients (Slottje 1991); or (b) based on weights defined by consultations with experts (Gwartney et al. 1996), decision makers (Vigerstol 2002) or by researcher expertise (Giorgi and Mearns 2002). For the Rio Grande/Rio Bravo, weights are obtained through the water demand (Equation 3-15) considering that: (a) the necessities of the water users and the environment can be expressed in the water demand value; (b) interviews with authorities and water users tend to agree with this formulation; and (c) other performance criteria are functions of the water demand value, i.e., reliability; or the performance criteria are scaled (normalized) using the water demand, i.e., vulnerability, maximum deficit and standard deviation. Not all the necessities of the water users are expressed in their water demand; however, an important part of the water users and environmental concern is expressed in this value.

3.3 INTEGRATION OF RESULTS

Results can be presented in matrix form. The Performance Criteria Matrix (*PCM*) contains the results of the *M* performance criteria for the i^{th} water users (Equation 3-17). The PCM has i^{th} rows and *M* columns.

$$PCM = \left[C_{i,m}\right]_{i\times M} = \begin{bmatrix} \mathrm{C}_{\mathrm{User\ 1,m}} & \cdots & \mathrm{C}_{\mathrm{User\ 1,M}} \\ \vdots & \ddots & \vdots \\ \mathrm{C}_{\mathrm{User}\ i\mathrm{,m}} & \cdots & \mathrm{C}_{\mathrm{User}\ i\mathrm{,M}} \end{bmatrix} \qquad \text{Equation 3-17}$$

The Sustainability Index Matrix (SIM) contains the results of the sustainability index for the i^{th} water users (Equation 3-18). The SIM matrix has i^{th} rows and one column. Notice that the SIM reduce the *M* number of columns in the PCM to one column.

$$SIM = \left[Sust_{i,1}\right]_{i\times 1} = \begin{bmatrix} \mathrm{Sust}_{\mathrm{User\ 1}} \\ \vdots \\ \mathrm{Sust}_{\mathrm{User}\ i} \end{bmatrix} \qquad \text{Equation 3-18}$$

The Relative Sustainability Matrix (RSM) contains the results of the relative sustainability index for *K* number of groups. Each group *k* is integrated of water users from *i* to *j*. Notice that the RSM reduce the number of rows in the PCM to *K* number of rows.

$$RSM = [Rel.Sust_k]_{K\times 1} = \begin{bmatrix} \mathrm{Rel.\,Sust}_{\mathrm{Group\ 1}} \\ \vdots \\ \mathrm{Rel.\,Sust}_{\mathrm{Group\ K}} \end{bmatrix} \qquad \text{Equation 3-19}$$

Figure 3-1 shows the PCM, SIM and RSM for Group *k* of water users from *i* to *j*, whose performance criteria C are from m to M. This figure illustrates how the sustainability index matrix (SIM) reduces the number of columns in the performance criteria matrix (PCM) by calculating a geometric average of the performance criteria. Similarly, the number of rows in the sustainability index matrix (SIM) is reduced in the relative sustainability matrix (RSM) by calculating a weighted average of individual sustainability indices.

$$PCM = \begin{bmatrix} \mathrm{C}_{\mathrm{User}\ i,m} & \cdots & \mathrm{C}_{\mathrm{User}\ i,\mathrm{M}} \\ \vdots & \ddots & \vdots \\ \mathrm{C}_{\mathrm{User}\ j,m} & \cdots & \mathrm{C}_{\mathrm{User}\ j,\mathrm{M}} \end{bmatrix} \rightarrow SIM = \begin{bmatrix} \mathrm{Sust}_{\mathrm{User}\ i} \\ \vdots \\ \mathrm{Sust}_{\mathrm{User}\ j} \end{bmatrix} \rightarrow RSM = \left[Rel\ Sust^{\mathrm{Group}\ k} \right]$$

Figure 3-1: Performance Criteria Matrix (PCM), Sustainability Index Matrix (SIM) and Relative Sustainability Matrix (RSM)

Chapter 4 Application: Rio Grande/Rio Bravo Basin

This chapter explains the water management principles of the Rio Grande/Rio Bravo basin and how the methodology proposed in Chapter 3 has been used for system requirements (treaty obligations), water users in the US, Mexico and environmental requirements. First, the international agreements are presented, describing the water division between the United States and Mexico and defining the sustainability index for these system requirements. Second, the water allocation system for Mexico and the US is presented defining the sustainability index for these water users. Finally, the sustainability index for environmental requirements is defined.

4.1 International Agreements

Two international agreements establish the water division between the United States and Mexico: the Convention of 1906 and the Treaty of 1944.

4.1.1 Convention of 1906

The 1906 Convention between the United States and Mexico specifies the allocation of water of the Rio Grande/Rio Bravo from the El Paso/Ciudad Juarez valley to Fort Quitman, Texas. According to this convention, the United States must deliver 74 million m^3/year to Mexico from Elephant Butte dam (IBWC 1906). This water is used to supply water to irrigation district DR-009 Valle de Juarez. For the United States, water from Elephant Butte dam is allocated according to the Rio Grande Compact to the Elephant Butte Irrigation District in New Mexico and the El Paso County Water Improvement District #1 in Texas with water rights of 542 million m^3/year and 480 million m^3/year, respectively (IBWC DEIS 2003a and 2003b).

4.1.2 Treaty of 1944

The 1944 treaty between United States and Mexico specifies the water allocation for the Rio Grande/Rio Bravo, Colorado and Tijuana rivers (IBWC 1944). Articles 4 though 9 define the Rio Grande/Rio Bravo water allocation for both countries below Ft. Quitman, Texas. The *United States* has the ownership of: (1) all the waters reaching the Rio Grande/Rio Bravo from the Pecos and Devil Rivers, Goodenough Spring, and Alamito, Terlingua, San Felipe and Pinto Creeks; (2) one third of the flow reaching the Rio Grande from the six Mexican tributaries Rio Conchos, San Diego, San Rodrigo, Escondido, Salado and Arroyo Las Vacas, provided that this third shall not be less than 431.721 million m^3/year as an average over cycles of 5 consecutive years; and (3) one half of all other flows not otherwise allotted along the Rio Grande/Rio Bravo. *Mexico* has the ownership of: (1) all the waters reaching the Rio Grande from the San Juan and Alamo Rivers, including the return flows from lands irrigated from these rivers; (2) two thirds of the flow reaching the Rio Grande/Rio Bravo from the six Mexican tributaries named above; and (3) one half of all other flows not otherwise allotted occurring along the Rio Grande/Rio Bravo.

Amistad and Falcon international dams are used to store and manage the water for both countries and each country has its own storage account in each reservoir. Amistad dam has a conservation capacity of 3,887 million m^3 of which 56.2% belongs to the U.S. and 43.8% belongs to Mexico. Falcon dam has a conservation capacity of 4,889 million m^3 of which 58.6% belongs to the United States and 41.4% belongs to Mexico. The treaty cycles mentioned above can expire in less than five years if the U.S. storage in both dams is filled with water belonging to the United States.

The Mexican water deliveries specified in the treaty must be fulfilled with the one-third outflow of the six Mexican tributaries listed above. At the end of a 5-year cycle, the delivery from these tributaries is evaluated to determine the accomplishment of the treaty obligations. If there is a deficit in the treaty delivery, this deficit must be paid in the following cycle primarily with the one-third outflow of water coming from the six tributaries and extraordinarily, if the Mexican and the U.S. section of the IBWC agrees, with the Mexican portion of the six tributaries and with transfers of water from the Mexican storage in the international dams (IBWC 1969).

The sustainability index proposed for the treaty obligations is:

$$Sust^{Treaty} = [Rel^{Treaty} * Res^{Treaty} * (1 - Vul^{Treaty}) * (1 - \sigma^{Treaty})]^{1/4} \quad \text{Equation 4-1}$$

Four out of the six Mexican tributaries delivering water to the treaty are unregulated rivers (Arroyo Las Vacas, San Diego, San Rodrigo and Escondido). In addition, there is no defined policy in the two regulated rivers (Rio Conchos and Salado) to deliver water to meet treaty obligations; in practice, only the gains of the reach between the most downstream reservoir in each tributary (Luis L. Leon dam in Rio Conchos and Venustiano Carranza dam in the Rio Salado) and the Rio Grande/Rio Bravo confluence are left in the river to met the treaty obligations. Sporadically, spills from these reservoirs will contribute to the delivery of treaty obligations. Thus, in practice, the treaty obligations are supplied by natural means. Because of this, the standard deviation criterion (σ^i) is used to assess the variability of the treaty obligations and to help identify adaptation policies that reduce the variability of treaty deliveries, providing a more steady delivery of treaty water by increasing low flows during drought periods and reducing spills during wet periods. The standard deviation for the treaty obligations (σ^{Treaty}) is calculated from the annual deliveries of the 6 Mexican tributaries.

4.2 MEXICO

On the Mexican side of the Rio Grande/Rio Bravo, the National Water Commission "Comisión Nacional del Agua" (CONAGUA) is the federal authority responsible for water management. CONAGUA carries out water planning and management along the border according to the accounting of water provided by the IBWC.

Mexican water demands are characterized by use. In this research are considered only agricultural, domestic, municipal and other water users, accounting for the 99.2% of the total Mexican water demand (CONAGUA 2004). The National Waters' Law of Mexico "Ley de Aguas Nacionales" establishes the priority for all water uses (CONAGUA, 2008.a). Municipal and domestic users have the highest priority and two times their annual water demand must be stored in the reservoirs. Agricultural users are not guaranteed and their allocation depends on the available storage in the respective dam that supplies them. Each October, CONAGUA determines the available reservoir storage, after deducting municipal allocations, evaporation and operation losses (Collado 2002). Then, a negotiation between CONAGUA and the irrigation districts sets the agricultural water allocation for the coming water year. Since 2002, CONAGUA has tried to deliver the users' annual water concession (legal definition of water rights in Mexico) if there is enough water in the available storage in the respective reservoirs, if not, a shortage in the water delivery is negotiated.

The sustainability index proposed for Mexican water users is

$$Sust^{MX\,i} = \left[Rel^{MX\,i} * Res^{MX\,i} * \left(1 - Vul^{MX\,i}\right) * \left(1 - MaxDef^{MX\,i}\right)\right]^{1/4} \qquad \text{Equation 4-2}$$

The Rio Grande/Rio Bravo is a naturally water scarce basin (SEMARNAT 2004), extended and severe periods of drought have occurred in the basin. During the latest drought (1994-2003), Mexico was not able to deliver the treaty water to the U.S. in two consecutive cycles of the 1944 treaty: cycle 25 (1992-1997) and cycle 26 (1997-2002). In order to cover these deficits, extraordinary measures were taken by the authorities, such as stopping the supply for Mexican irrigations districts 025 Bajo Rio Bravo and 004 Don Martin for two years (2002 and 2003) and transferring Mexican storage in the international reservoirs to the U.S. (IBWC 2001 and 2002). These decisions severely affected Mexican agriculture water users in the basin, almost extinguishing this activity in the lower part of the basin. Because of this, the Maximum Deficit criterion ($MaxDef^i$) is included in the sustainability index for Mexican water users. The aim of this criterion is to help identify adaptation policies that not only reduce the expected deficit ($1 - Vuln^i$) but also the maximum deficit that they may experience ($1 - MaxDeficit^i$). Reliability, Resilience, Vulnerability and Maximum Deficit are calculated based on the annual water supply to Mexican users.

4.3 United States

In the U.S., the Texas Commission on Environmental Quality (TCEQ) is the state agency in charge of water management in Texas. The Texas Rio Grande Watermaster Program regulates the U.S. water diversion from Amistad reservoir to the Gulf of Mexico (TCEQ 2005a). TCEQ performs water planning and management along the U.S. Rio Grande portion of the river according to the accounting of water provided by the IBWC.

The Texas Water Master allocates water on an account basis (TCEQ 2006) according to five water use types: irrigation, municipal, mining, industrial and other.

Below Amistad reservoir water rights are divided into Type A and B according to the Texas Watermaster Rules. Municipal and industrial users have the highest priority and they are guaranteed an amount for each year. The rest of the users are not guaranteed and their allocation depends on the water remaining in their accounts from the previous year. Every month the Texas Water Master determines the amount of unallocated water in the U.S. account of the international reservoirs after the municipal and industrial allocation has been subtracted. If there is surplus water remaining, it is allocated to agricultural users of Type A, then Type B, then mining and finally other uses.

The sustainability index proposed for U.S. water users is

$$Sust^{US\,i} = \left[Rel^{US\,i} * Res^{US\,i} * \left(1 - Vuln^{US\,i}\right) * \left(1 - MaxDef^{US\,i}\right)\right]^{1/4} \qquad \text{Equation 4-3}$$

Similarly to Mexico, agriculture and mining water users in the U.S. suffered shortages in their water demand during the last drought (1994-2003). Because of this, the Maximum Deficit criterion ($MaxDef^{i}$) is also included in the sustainability index for U.S. water users. The water management for the U.S. is executed by month; water planning models used by the TCEQ (Brandes 2004) require that the time-based and volumetric reliability are calculated in monthly time steps. Thus, reliability, resilience, vulnerability and maximum deficit for U.S. water users are calculated in monthly time steps.

4.4 ENVIRONMENT

In the Rio Grande/Rio Bravo basin, environmental flows are not considered an integral part of water management. During the planning, negotiation and distribution of water in the treaties, environmental needs of native ecosystems were not explicitely considered (Orive-Alba 1945, Enriquez-Coyro 1976, Collado 2002). In the Convention of 1906 (IBWC 1906), the treaty of 1944 (IBWC 1944) and the Rio Grande Compact (TCEQ 1938); water distribution and allocation exclusively obeys human requirements, considering neither environmental flows nor a priority assigned to the environment. However, this inattention can/may change in the future, in the treaty of 1944 (Article 3) environmental requirements could be included as a beneficial use; furthermore, the Article 3 can be modified using a minute to re-order the water use priority in the basin.

Several efforts have been undertaken by individuals, government agencies and non-governmental organizations to determine the environmental flows required for the basin (Sandoval-Solis and McKinney 2009). In the Rio Conchos sub-basin, the World Wildlife Fund estimated the environmental flows at 9 locations (WWF 2006). These flows are used to evaluate the performance of the environmental requirements.

The sustainability index proposed for the environmental flows is

$$Sust^{Env,i} = \left[Rel^{Env,i} * Res^{Env,i} * \left(1 - Vuln^{Env,i}\right) * \left(1 - MaxDef^{Env,i}\right)\right]^{1/4} \qquad \text{Equation 4-4}$$

During droughts the environment suffers to meet its water requirements; usually, extreme low streamflows happen in these periods affecting the health of aquatic and riparian ecosystems. For this reason the Maximum Deficits criterion is included in Eq. 4-4. The Sustainability Index proposed for the environment considers essential to provide environmental flows frequently (Reliable), that if deficits happen, the expected (1-

Vulnerability) and maximum deficits (1-Maximum Deficit) are small, and that the system recover fast from deficits (Resilient). Since the environmental flows were aggregated monthly (Chapter 6.2.5), the performance criteria for the environment are calculated based on the monthly environmental flow supply. Because of the monthly time step characteristic of the Rio Grande/Bravo WEAP model, daily performance criteria are not evaluated, such as: a) the daily exceedance duration of a monthly indicator flows (i.e., 50%, 80% and 90% exceedance percentile flows), b) duration and number of spells of flows less than low flow threshold (i.e., duration of flows lower than 0.01 m^3/s), c) average recurrence interval of high daily flows (i.e., daily flows with return period of 1.5, 5 and 20 years in natural conditions) (Brizga et al. 2002). Further research is needed to build a daily time step model to properly assess the supply of environmental requirements in the basin.

Chapter 5 Water Resources Planning Model

A water resources planning model of the Rio Grande/Rio Bravo basin is used to evaluate the current and proposed water management policies. The Rio Grande/Rio Bravo WEAP model is a hydrologic planning simulation model that represents the water management in the basin (Danner et al. 2006). The Water Evaluation and Planning System (WEAP) (SEI 2010) is used to model water management in the Rio Grande/Rio Bravo basin. In the first part of this chapter the Rio Grande/Rio Bravo WEAP model is presented and compared with other planning models already built for the basin. In the second part of this chapter is described the characteristics of the Rio Grande/Rio Bravo WEAP model, such as period of analysis, the input data, infrastructure, operation and model testing. Details of WEAP and its application to other basins can be found in Yates *et al*. (2005a and 2005.b) and Purkey *et al.* (2007).

5.1 Introduction

Several agencies and institutions have built models of the Rio Grande/Rio Bravo basin or its sub-basins for different purposes: sediment transport (TAMU 1996), groundwater interaction (Bartolino and Cole 2002), dispute resolution (Tate 2002), water availability (Brandes 2003a), water management (Stewart et al. 2004, Gastelum et al. 2009), reservoir operations (US ACE 2004), drought management (Vigestol 2002, Gastelum 2006), rainfall-runoff response for historic (IMTA 2005) and future climate change conditions (Ingol-Blanco and McKinney 2008), among others. In this sense, the Rio Grande/Rio Bravo WEAP model is a water planning model intended to help in the dispute resolution, policy and decision making as did the OASIS (Tate 2002) and Stella (Vigerstol 2002) models, for the whole basin and not only for the Rio Conchos (Gastelum

2006), but with a solid calibration and validation of the model. The Rio Grande/Rio Bravo WEAP model is based on a firm understanding of the water allocation rules, water demands, regulations and international agreements that apply in different regions for both countries.

5.2 PERIOD OF ANALYSIS

The period of analysis is 60 years, from October 1940 to September 2000. The Rio Grande/Rio Bravo WEAP model carries out its simulation according to the water year (October – September), when the water authorities decide the amount of water to be allocated for each user. This period of analysis contains the historical drought record of the 1950's (1947-1957), the drought of the 1960's (1961-1965), the abundant water period of the 1970's and 80's (1966-1993) and part of the most recent drought of the 1990's (1994-2007). Hydrological input data, such as, naturalized flow, evaporation, stream flow data, and reservoir storages etc., are available for this period. The main source for hydrologic, hydraulic and related data for the model is the Rio Grande/Bravo geodatabase (Patino-Gomez et al., 2007).

5.3 HYDROLOGIC DATA

The data used in the Rio Grande/Rio Bravo WEAP model comes from different agencies in both countries. Main tributary headflows and inflows along the reaches were taken from two sources: (1) the "naturalized stream flow" data for the Rio Grande basin developed for the TCEQ by the R. J. Brandes Company (2003a) and (2) from the "annual naturalized flow data" calculated in the Annual Water Availability study for the Rio Bravo published by CONAGUA (2008.b). A total of 21 headflows and 22 incremental inflows along the reaches are included in the Rio Grande/Rio Bravo WEAP model. The model contains channel loss factors for the river reaches accounting for conveyance, evaporation, evapotranspiration and seepage losses (IBWC 2005; CONAGUA 2007; and Brandes 2003b). Details of the model components, coefficients and performance are available in Danner *et al*. (2006).

5.4 WATER DEMANDS

The Rio Grande/Rio Bravo WEAP model includes 216 water demands (Table 5-1). U.S. water demands are divided into five water use types: agricultural, municipal, mining, industrial and other. Also, below the international reservoirs Amistad and Falcon, Texas water rights are divided into Type A and B based on the Texas Watermaster Allocation logic (TCEQ 2005a). U.S. water demands in the model were derived from the TCEQ (2005b) and the Rio Grande Compact (IBWC DEIS 2003a and 2003b). Annual demands used in the model correspond to 62% of the full allocation demand (personal communication, Carlos Rubenstein, Commissioner, TCEQ, October 2009) and these are disaggregated into monthly values, according to the distributions estimated by TCEQ (Brandes 2003a).

Mexican water demands are characterized by use. In the model, only agricultural, municipal and other water users are considered because they represent the 99% of the total consumptive water use for Mexico (CONAGUA 2004). The priority for all water users is established in the National Waters' Law (CONAGUA 2008.a). Mexican water demands were derived from the public database of water rights (CONAGUA 2004), which is the official database of CONAGUA. For Mexico, annual water uses for 2004 were disaggregated into monthly values. Return flow factors were derived from TCEQ

(2005b), IMTA (Collado, 2002) CONAGUA (CONAGUA 2004), and water users (CONAGUA 2005, L. R. Caballero, private communication May 2005).

Table 5-1: Water Demands considered in the Rio Grande/Rio Bravo WEAP Model

Water Use	Demands	Mexico	United States
Municipal	Number	21	23
	(Million m^3/year)	731	283
Irrigation	Number	39	53
	(Million m^3/year)	3,881	3,034**
Other*	Number	1	20
	(Million m^3/year)	47	11
Groundwater	Number	35	21
	(Million m^3/year)	1,852	2,840***
Total	Number	96	120
	(Million m^3/year)	6,511	6,168

* This category includes Industrial, Mining and Other water uses.
** Full Allocation Demand for U.S. water demands. The current conditions are 62% of the Full Allocation Demand.
*** This value represents an Upper bound on aquifer withdrawal by these water demands.

Due to the large number of individual water users along the river in both countries, many of the water demands were aggregated in the model. U.S. demands were aggregated based on use type, i.e., municipal, irrigation, etc, type of water right (A or B) and location in the basin relative to the river reaches defined by the TCEQ Rio Grande Watermaster. The Watermaster Rules define thirteen river reaches, referred to as Watermaster Sections (Brandes 2003a). Similarly, Mexican demands were aggregated also by type of use and location in the basin. Surface water and groundwater use in both countries is considered in the model. Most of the semi-formal irrigation districts in Mexico (called Urderales) and many of the individual water users in the U.S. use groundwater as their main source of water supply. Groundwater is represented in the model as simple “tanks” for each regional aquifer in the basin.

5.5 Infrastructure

There are twenty five reservoirs in the model with a total storage capacity of approximately 26.3 billion m^3 (Danner et al. 2006). Sixteen of the reservoirs are located in Mexico with a total storage capacity of about 11.4 billion m^3; six are in the U.S. with a total storage capacity of about 3.4 billion m^3; and three international reservoirs, Amistad, Falcon and Anzalduas (weir) with a total storage capacity of about 11.6 billion m^3 (CILA 2009).

5.6 Operation

The water allocation system represented in the Rio Grande/Rio Bravo WEAP model follows the allocation of water for Texas according to the Texas Administrative Code Title 30 Chapter 303 (TCEQ 2006), for Mexico according to the National Waters' Law (CONAGUA 2008.a), and along the border it follows the international allocation of water established in the Convention of 1906 (IBWC 1906) and the Treaty of 1944 between Mexico and the U.S. (IBWC 1944). The model contains rules to replicate the accounting and allocation logic of the 1944 U.S.-Mexico Treaty. This logic includes: tracking inflows from the treaty tributaries; allocating those flows to the respective countries; accounting for storage for each country in the international reservoirs; calculating evaporation losses for each country; accounting of the Mexican treaty deliveries per year and cycle, and resetting treaty cycles when the international reservoirs are filled.

5.7 MODEL TESTING

Although the model contains inflow data for sixty years, model calibration was done for 15 years, from October 1978 to September 1993. During this period construction of most of the basin infrastructure had been completed, including both international dams. Even though there was no specific water allocation policy in Mexico during this period, the record of historic diversions exists for almost all of the water users. For Mexico, historical diversions were provided by CONAGUA (2008.b) and for the U.S. these data were derived from the IBWC withdrawal records available online (IBWC 2009). This section briefly describes the testing process for the Rio Grande/Rio Bravo WEAP model which includes the calibration and validation procedures. A complete description of this process is presented in Danner *et al*. (2006).

5.7.1 Calibration

In general, two important sets of parameters were used to calibrate the Rio Grande/Rio Bravo WEAP model: the conveyance losses along the streams and the rules governing the release of water from the conservation pools of the dams.

At least two sets of conveyance losses factors are available for the Rio Grande/Rio Bravo basin, one set from CONAGUA (Collado 2002, Aldama 2008) and other set from TCEQ (Brandes 2003b). The set of conveyance losses that provided the best model performance is the following: on Mexican streams the CONAGUA conveyance losses are used; on U.S. streams and along the Rio Grande/Rio Bravo main-stream the TCEQ conveyance losses are used. The decision to use the TCEQ conveyance losses along the Rio Grande/Rio Bravo stream is supported by the fact that this set considers the evaporation and plant uptake losses, including the salt cedar effect along the river, as well as the geology and hydrogeology for each reach; the CONAGUA conveyance losses do not consider these factors.

Regarding the conservation pools of the dams, the conservation storage for all the U.S. dams is well defined; however, this value varies seasonally for the Mexican and international dams. For dams in Mexico, it usually varies as follows: the normal conservation storage is used in the rainy season, June 1st to October 31st; meanwhile a larger and undefined conservation storage is used for the rest of the year. An historic analysis of the dam storages was done in order to define the conservation pool value for each Mexican and international dam.

One of the main uncertainties in the model is the conveyance losses along the reaches, mostly during drought periods. The conveyance losses provided in the two available datasets, CONAGUA and TCEQ, are fixed values along the time. These values were estimated considering normal conditions (Collado 2002, Brandes 2003b). As a result, under drought periods these values underestimate the losses in the system. Several runs were done in order to estimate the variation of the conveyance losses as a function of the hydrologic conditions; however, due to the lack of data during drought periods it was not possible to obtain this relationship. Further research is needed regarding the conveyance losses in the basin as a function of the hydrologic conditions. A more detailed explanation about the calibration process is provided in Danner et al (2006).

5.7.2 Validation

A *Historic Scenario* was developed to evaluate the accuracy of the model; model results were compared to historical values for reservoir storage and gauged stream flow. A 15-year hydrologic period of analysis was used for this scenario (October 1978 to

September 1993). This period was selected because both international dams were in existence and operating. The historic water demands of this period were loaded into the model and results from streamflows and reservoir storage were compared with the historic data. Water demands in this period varied from year to year; historical Mexican demands for municipalities, irrigation districts and private users were provided by CONAGUA (CONAGUA 2008.b) and the U.S. demands were derived from the IBWC withdrawal records from all the Water Master Sections (IBWC 2009). Figure 5-1 and Figure 5-2 show the historic water demands loaded into the model in the *Historic* scenario for the U.S. and Mexico, respectively.

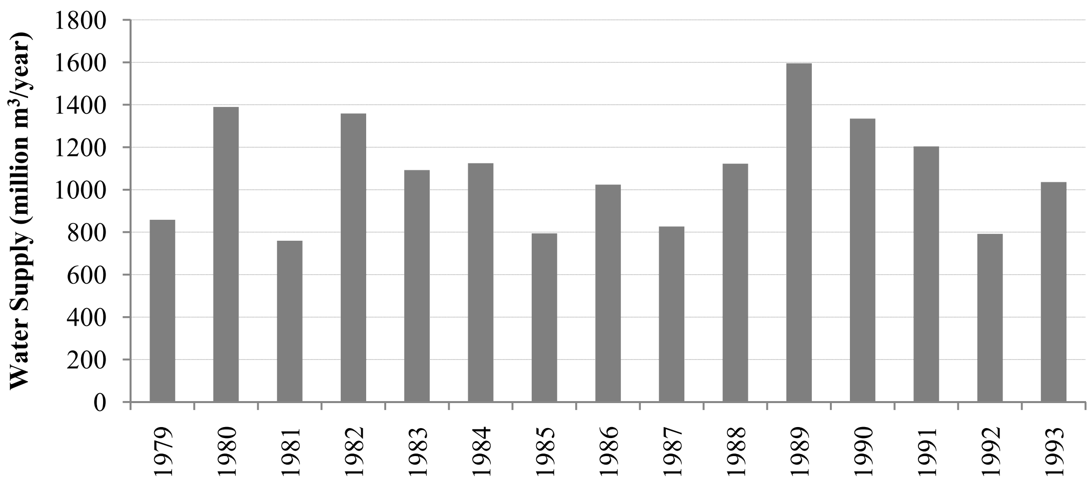


Figure 5-1: Historic water supply for U.S. demands

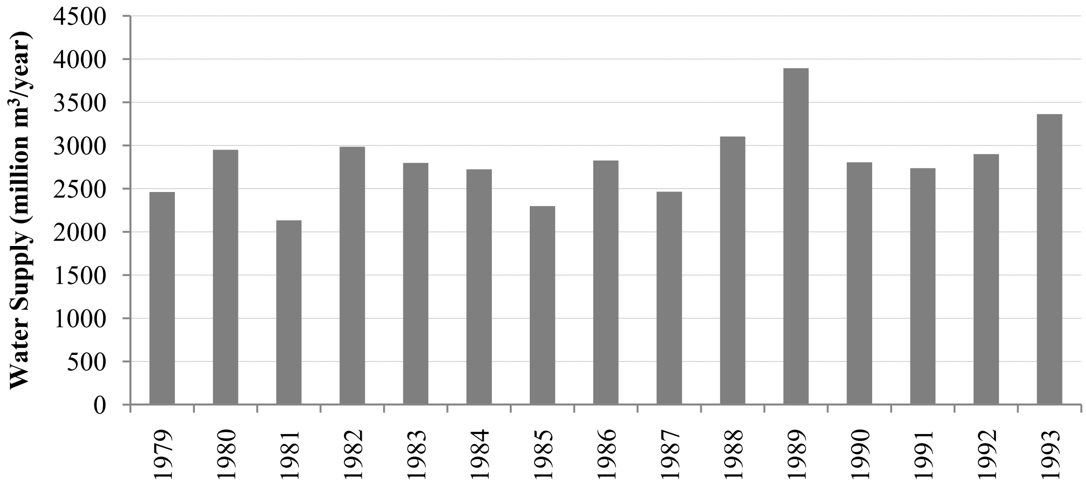


Figure 5-2: Historic water supply for Mexican demands

The conveyance losses along the streams and the rules governing the releases of water from conservation pools were adjusted in order to match streamflows at different stations and reservoir storages given the historic water supplies. Danner et al. (2006) presents the comparison of the historic and the model values for 12 reservoir storages and 8 streamflow gages. During the calibration and validation process, the storage in the international reservoirs Amistad and Falcon were used as indicators to evaluate the performance of the model because: (a) they store the water for each country according to the treaty of 1944; and (b) both reservoirs are influenced by the water management in the entire basin. Thus, if there is a problem in the modeling of certain region or with the water for each country, the storage in the international reservoirs shows it immediately.

Amistad's inflows depend on the water management in the Conchos and Pecos basin as well as the water coming from the Devils and Fort Quitman; Amistad's outflows depend on the water releases for water users upstream Falcon and transfers of water to Falcon. Falcon's inflows depend on the water transfers from Amistad and the water management in Las Vacas, San Diego, San Rodrigo, Escondido and Salado rivers;

Falcon's outflows depend on the water releases for the lower Rio Grande Valley and the water coming from San Juan River. Thus, the model can be evaluated using the storage at these reservoirs. Figure 5-3 and Figure 5-4 show a comparison of the international dam storage calculated by the model and the historic data for Mexico and the U.S., respectively.

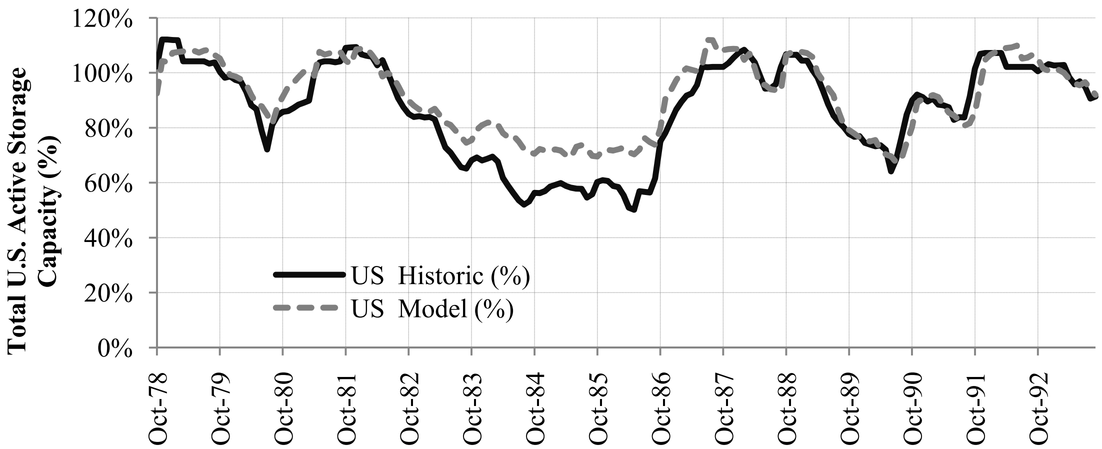


Figure 5-3: U.S. storage in the international dams; Model versus Historic

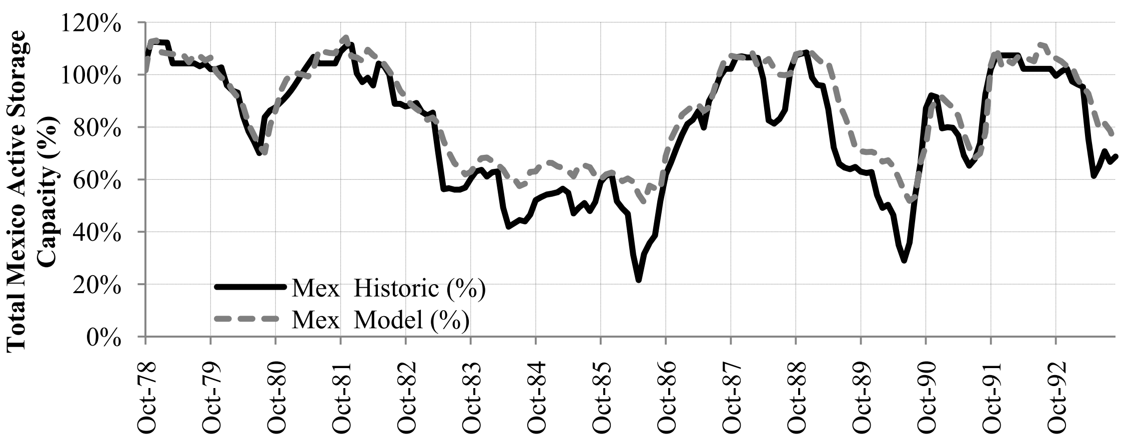


Figure 5-4: Mexican storage in the international dams; Model versus Historic

Two coefficients are used in the storage at the international reservoir for each country to evaluate the goodness of fit for the model validation (Legates and McCabe 1999): the coefficient of efficiency (*E*) shown in Equation 5-1 (Nash and Sutcliffe 1970) and the coefficient of agreement (*d*) shown in Equation 5-2 (Willmott et al. 1985). These coefficients compare the observed values (O_t) against the predicted values (P_t) from the model at time step *t*, over *n* number of total time steps.

$$E = 1.0 - \frac{\sum_{t=1}^{t=n}(O_t - P_t)^2}{\sum_{t=1}^{t=n}(O_t - \bar{O})^2} \qquad \text{Equation 5-1}$$

$$d = 1.0 - \frac{\sum_{t=1}^{t=n}(O_t - P_t)^2}{\sum_{t=1}^{t=n}(|P_t - \bar{O}| + |O_t - \bar{O}|)^2} \qquad \text{Equation 5-2}$$

where:

$$\bar{O} = \frac{1}{n}\sum_{t=1}^{t=n} O_t \qquad \text{Equation 5-3}$$

The coefficient of efficiency (*E*) ranges from minus infinity to 1, with higher values indicating better agreement. The index of agreement (*d*) varies from 0 to 1 with higher values indicating a better agreement between the model and the observations (Legates and McCabe 1999). The coefficients of efficiency for Mexico and the U.S. are 0.825 and 0.805, respectively; meaning that the mean square error (i.e. the squared differences between the observed and model values) is 17.5% and 19.5% of the variance in the observed data. The coefficients of agreement for Mexico and the U.S. are 0.953 and 0.945, respectively; meaning that the mean square error is 4.7% and 5.5% of the potential error ($\sum_{t=1}^{t=n}(|P_t - \bar{O}| + |O_t - \bar{O}|)^2$). The potential error is the largest value that $(O_t - P_t)^2$ can attain for each observation/model simulation pair. In both coefficients, the difference between the observed and predicted value (in fact, the mean square error) is small compared to the variance or the potential error. Both coefficients show that the Rio Grande/Bravo WEAP model is adequately representing the water resource system; the mean square error is less than 20% of the observed variance of the data, and less than 6% of the potential error.

Chapter 6 Water Management Scenarios

In this chapter are described the water management scenarios evaluated for the Rio Grande/Rio Bravo basin (NHI 2006b). First, the *Baseline* scenario is defined, which is the system with no policy implemented (before 2004). Then, the alternative water management scenarios are described in two groups; scenarios for the upper and lower basin. This section includes policies already implemented, such as the buyback of water rights through the PADUA program and improvement in infrastructure through Minute 309; as well as proposed policies, such as groundwater banking and environmental flows in the Rio Conchos sub-basin. Finally, the *Current* scenario is defined, which is the system as it is now, considering the policies already implemented (after 2004). Results of the no policy scenario (*Baseline* Scenario) and all the scenarios described in this chapter are presented in the chapter seven.

6.1 Baseline Scenario

The Baseline scenario is the system without any policy implemented. This scenario follows the water management principles already explained: the division of water between the U.S. and Mexico according to the Convention of 1906 and the Treaty of 1944; in the U.S. according to the Texas Rio Grande Water Master Program; and in Mexico according to the National Water's Law. The *Baseline* scenario is the water management before 2004. For U.S. water user is considered the 70% of the full allocation demand; for Mexico is considered the water demand in 2004. The aim of this scenario is used to evaluate the benefits and negative effects of the proposed policies in the basin.

6.2 Upper Basin Scenarios: Rio Conchos Sub-basin

For the Rio Conchos sub-basin, the PADUA program and the water conservation measures described in IBWC Minute 309 are two policies already implemented. Groundwater banking through the *In Lieu* method and the delivery of environmental flows are two policies proposed in this research.

6.2.1 PADUA Program

In 2003, the Mexican Ministry of Agriculture, Livestock, Rural Development, Fisheries and Food (SAGARPA from its acronym in spanish) made public the PADUA program (Programa de Adecuación de Derechos de Uso del Agua y Redimensionamiento de Distritos de Riego) (SAGARPA 2003). The objective of this program is to buy back water right titles conferred to irrigation districts that under drought conditions would be impossible or hard to supply from surface water and groundwater, for either economic or hydrological conditions (SAGARPA-FAO 2005).

Table 6-1: Water Rights Bought Back Under the PADUA Program

Irrigation District	Water Source	Water Demand Before PADUA ($1x10^6$ m^3/year)	Water Demand After PADUA ($1x10^6$ m^3/year)	Water Bought Back ($1x10^6$ m^3/year)
005 Delicias	Surface	941.6	850.3	91.3
	Groundwater	189.0	170.7	18.3
090 Bajo Rio Conchos	Surface	85.0	63.7	21.3
	Groundwater	---	---	---
			Total	**130.9**

Table 6-2 shows the water demand before and after the implementation of the PADUA program, as well as the volume of water bought back in DR-005 Delicias and DR-090 Bajo Rio Conchos (see Figure 6-1). In irrigation district DR-005 Delicias 91.3

million m^3/year (74,000 acre-feet/year) of surface water rights and 18.3 million m^3/year (14,800 acre-feet/year) of groundwater rights were bought back. In irrigation district DR-090 Bajo Conchos 21.3 million m^3/year (17,300 acre-feet/year) of surface water rights were bought back. The total amount of water rights retired under the program was 130.9 million m^3/year (106,100 acre-feet/year) from which 112.6 million m^3/year (91,300 acre-feet/year) are of surface water and 18.3 million m^3/year (14,800 acre-feet/year) are of groundwater (SAGARPA 2005, SAGARPA 2006 and SAGARPA 2007).

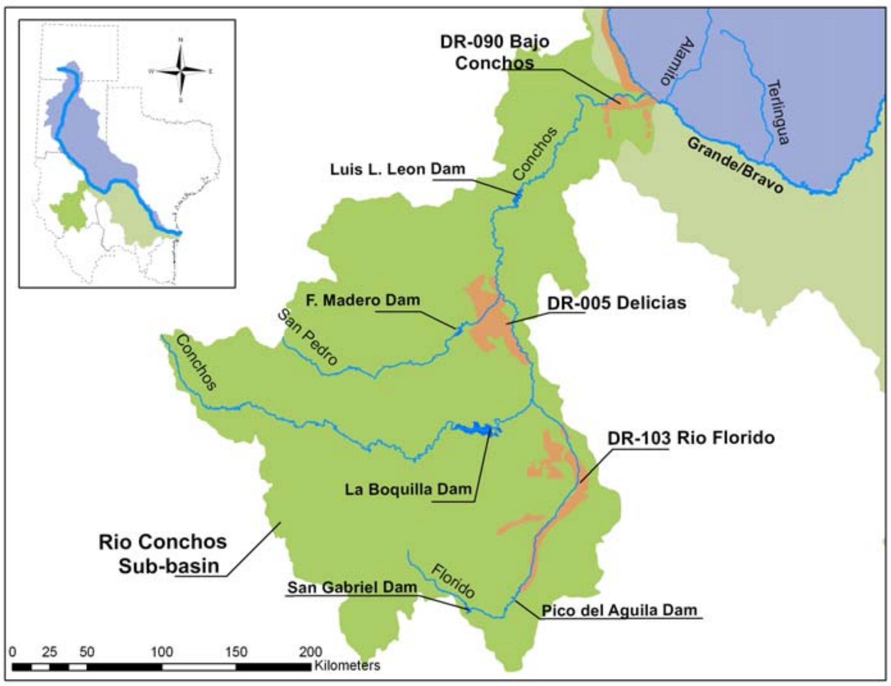


Figure 6-1: Irrigation Districts in the Rio Conchos Basin

Table 6-2 shows the investment when the PADUA program was implemented and an estimate present value for a policy similar to the PADUA program. From 2004 to 2006, surface and ground water right bought back occurred at \$159 and \$198 per 1,000 m^3, respectively (\$2,000 and \$2,500 pesos per 1,000 m^3 of surface and groundwater rights, respectively; monetary exchange 12.6 pesos per dollar). These cost of surface and groundwater in the present year (2011) considering an annual interest rate of 6.5% are \$217 and \$272 per 1,000 m^3, respectively (\$2,740 and \$3,425 pesos per 1,000 m^3 of surface and groundwater rights, respectively; monetary exchange 12.6 pesos per dollar). The total investment of this policy in present value is \$29.5 million dollars. For this research, the PADUA program will be used as the initial parameter in the scenarios related to the permanent buy-back of water rights in the basin.

Table 6-2: Investment in the PADUA Program

Irrigation District	Water Source	Investment in 2006* (\$ Million)	(A) Investment in 2011** (\$ Million)	(B) Water Bought Back ($1x10^6$ m^3/year)	(A / B) Cost per million of water saved (\$ Million)
DR-005	Surface	14.5	19.8	91.3	0.217
	Groundwater	3.6	5.0	18.3	0.272
DR-090	Surface	3.4	4.6	21.3	0.217
	Groundwater	---	---	---	---
	Total	21.5	**29.5**	130.9	0.225

* \$159 and \$198 per 1,000 m^3 (\$2,000 and \$2,500 pesos) of surface and groundwater rights, respectively; monetary exchange 12.6 pesos per dollar
** \$217 and \$272 per 1,000 m^3 (\$2,740 and \$3,425 pesos) of surface and groundwater rights, respectively; annual interest rate 6.5%; monetary exchange 12.6 pesos per dollar

6.2.2 Reduction of DR-005 Delicias to 50,000 hectares

One of the scenarios proposed is the reduction of the agriculture area of irrigation district 005 Delicias from 90,000 to 50,000 hectare. This reduction goes beyond what was considered when the 1944 Treaty was signed, since in that time DR-005 Delicias was considered to be 71,500 ha of agriculture land (IBWC 1946). A linear relationship of the irrigated area and the water demands was used to obtain the water demand for 50,000 ha.

Considering that to supply water for 90,000 ha it is necessary a water demand of 1130.546 million m^3/year (917,000 acre-feet/year), in order to supply water for 50,000 ha is necessary 628.081 million m^3/year (509,000 acre-feet/year).

Table 6-3 show the surface and groundwater buybacks, and the investment required to reduce irrigation district 005 Delicias from 90,000 ha to 50,000 ha. In 2006, when the PADUA program finished, the buyouts of surface and groundwater rights occurred at \$159 and \$198 per 1,000 m^3, respectively (\$2,000 and \$2,500 pesos per 1,000 m^3 of surface and groundwater rights, respectively; monetary exchange 12.6 pesos per dollar). These costs of surface and groundwater in the present year (2011) considering an annual interest rate of 6.5% are \$217 and \$272 per 1,000 m^3, respectively (\$2,740 and \$3,425 pesos per 1,000 m^3 of surface and groundwater rights, respectively; monetary exchange 12.6 pesos per dollar). The investment estimated for this policy is \$89 million.

Table 6-3: Water demands for DR-005 Delicias after reduction of the irrigated area to 50,000 ha.

Water Source	Water Demand After PADUA ($1x10^6$ m^3/year)	After Reduction ($1x10^6$ m^3/year)	Water Bought Back ($1x10^6$ m^3/year)	Price * (\$ per 1,000 m^3)	Investment (\$ Million)
Surface	850.3	523.1	327.2	217	71.2
Groundwater	170.7	105.0	65.7	271	17.8
Total	1021.0	628.1	392.9		**89.0**

*Monetary Exchange 12.6 pesos per dollar

Recent data for the 2008 water year (Oct/2007-Sep/2008) show that the irrigated area in DR-005 Delicias was 52,323 hectare with a diversion of 702 million m^3 (660 million m^3 from the reservoirs and 42 million m^3 from groundwater) (CONAGUA 2009).

The 2008 water year is the year after the most recent drought (1994-2007) and according to CONAGUA (2009); this was an average year for agriculture land cultivated, considering a 39 year time series of data (1970-2008). Similar data is specified in the technical information card for DR-005 Delicias showing an estimated annual cultivated area of 49,574 hectare (CONAGUA 2003). These information shows that the proposed reduction in the irrigated area is reasonable for DR-005 Delicias.

The objective of this policy is to consolidate the irrigated area to a reasonable and sustainable size that by buying back water rights that are supplied in wet sea

6.2.3 IBWC Minute 309

On July 3rd 2003, the IBWC signed the Minute 309 that specifies a set of water conservations measures that will be implemented in irrigation districts in the Rio Conchos basin and the conveyance of the savings to the Rio Grande/Rio Bravo (IBWC 2003). This minute is part of a set of immediate and long-term actions taken in the drought of 1994-2003 (IBWC 2001 and 2002). The objective of the water conservation measures is to increase the global efficiencies in irrigation districts DR-005 Delicias, DR-090 Bajo Conchos and DR-103 Rio Florido. Basically, there are the two main ideas to save water. First, reduce the conveyance losses by lining main and lateral canals; and second, increase the application efficiency on the farms by installing low pressure supply systems, land leveling, and implementing sprinkler systems, among others (IBWC 2003). The conveyance of the water savings to the Rio Grande/Rio Bravo is specified to be each December and January.

In minute 309, the global efficiency is defined as the ratio of the water consumed to the water extracted from the water sources. The global efficiency is function of the conveyance and application efficiencies; and is expressed through Equation 6-1. Table 6-4 shows the volume extracted from the water sources, the global efficiencies and the water savings expected for the irrigation districts selected.

$$Global_{Eff} = Conveyance_{Eff} * Application_{Eff} \qquad \text{Equation 6-1}$$

Table 6-4: Water savings expected after the conclusion of Minute 309

Irrigation District	Baseline Volume ($1x10^6$ m^3/year)	Baseline Efficiency (%)	After Minute 309 Volume ($1x10^6$ m^3/year)	After Minute 309 Efficiency (%)	Expected Savings ($1x10^6$ m3/year)
005 Delicias	857	33	514	55	**343**
090 Bajo Rio Conchos	96	35	71	47	**25**
103 Rio Florido	91	33	63	48	**28**
Total	1044	---	648	**---**	**396**

Before the application of Minute 309, for irrigation district DR-005 Delicias the conveyance efficiency and application efficiency were estimated of 61% and 54% respectively. After the water conservation measures the conveyance efficiency and application efficiency are expected of 69% and 80% respectively (Collado 2002; Caballero 2005). For this policy, this research considers only the water conservation measures implemented in DR-005 Delicias. Irrigation districts DR-090 Bajo Conchos and DR-103 Rio Florido has not been considered yet because the available data is not enough to make acceptable assumptions about the global efficiency. Further research is needed to determine the conveyance and application efficiencies for DR-090 Bajo Rio Conchos and DR-103 Rio Florido.

Table 6-5 shows the investment made in 2004 and the required investment in present value to implement Minute 309. In 2004 the investment in DR-005 Delicias, DR-

090 Bajo Rio Conchos and DR-103 Rio Florido were $108, $9 and $5 million ($1,360, $110 and $65 million pesos; monetary exchange 12.6 pesos per dollar). These investments in the present year (2011) considering an annual interest rate of 6.5% are $168, $14 and $8 million for DR-005, DR-09 and DR-103 respectively ($2,113, $171 and $101 million pesos, respectively; monetary exchange 12.6 pesos per dollar). The investment estimated for this policy in the present year is $189 million.

Table 6-5: Investment spent in Minute 309

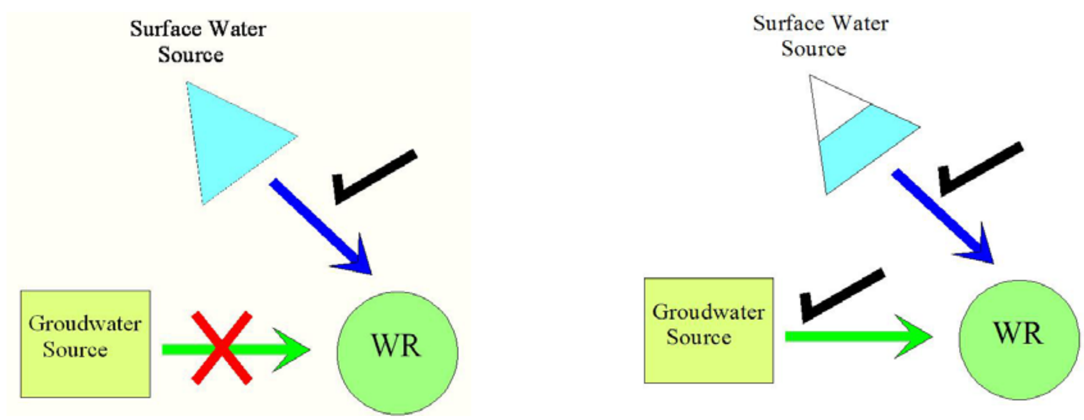
Irrigation District	Investment in 2004* ($ Million)	(A) Investment in 2011 ($ Million Pesos)	(B) Expected Water Savings (B) ($1x10^6$ m3/year)	(A / B) Cost per million of water saved ($ Million)
005 Delicias	108	168	343	0.489
090 Bajo Rio Conchos	9	14	25	0.543
103 Rio Florido	5	8	28	0.286
Total	122	**189**	396	0.478

*Monetary Exchange 12.6 pesos per dollar
*Monetary Exchange 12.6 pesos per dollar, Annual interest rate 6.5%

6.2.4 In Lieu Groundwater Banking in the Rio Conchos

In many regions, such as the Rio Grande/Rio Bravo (Wagner and Vaquero 2002), it has been recognized that surface and ground water must be managed conjunctively (Pulido-Velazquez et al. 2006) because of their hydraulic and operational inter-dependence. Conjunctive management of ground and surface water has been studied for some time (Buras 1963); mostly, as optimizations models for small (Pulido-Velazquez et al. 2006), medium (Reining et al. 1999) and large scale areas (McPhee et al. 2004). Groundwater banking is an area that relies on the conjunctive use of surface water and groundwater.

Groundwater banking through the *In Lieu* method stores natural recharge from surface water in aquifers. Consider a water user that has a right to two different water sources: surface water from a reservoir and groundwater from an aquifer. *Recharge* to a groundwater bank in the aquifer may take place in wet years, when there is sufficient surface water to supply the demand (Figure 6-2.a). In this case, aquifer pumping is stopped and natural recharge accumulates in the bank. The maximum water deposited in the groundwater bank is equal to the groundwater right.



a) Normal or high available storage in dams; dams supply all water demand.

b) Low available storage in dams; aquifer and dams supply water demand.

Figure 6-2: Scheme of the Groundwater Banking through the In Lieu Method

Extraction from the bank takes place in dry years, when there is insufficient surface water to supply the demand (Figure 6-2.b). In this case, water from the reservoir is used to supply as much water as it can, and water from the groundwater bank is pumped to cover the deficit. When modeling this, the groundwater storage is divided in two accounts: an aquifer account and a groundwater bank account. The aquifer account tracks the storage that would have been in the aquifer if the groundwater banking did not take place. In contrast, the groundwater bank account tracks the water deposits and withdrawals from the bank. *In Lieu* groundwater banking has three main characteristics: (1) water users that want to use this method must be supplied by at least two different water sources; (2) the operation of the bank depends on the surface water available to the water user; and (3) the accumulation in the bank by natural, rather than artificial, means.

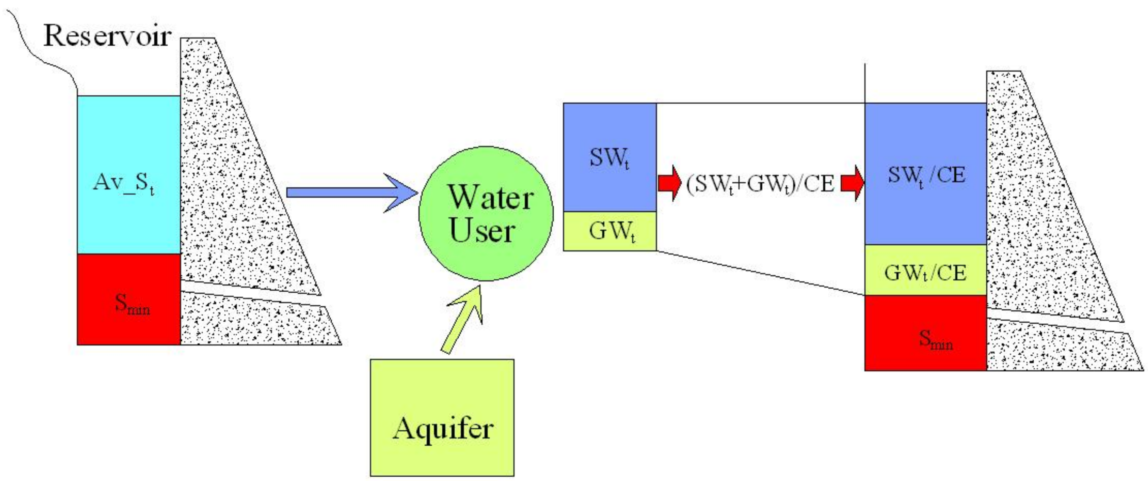


Figure 6-3: Scheme of water supply and diversion under the *In Lieu* groundwater banking method

Assume that in period *t,* water is supplied from a combination of surface water (SW_t) and ground water (GW_t), and that the conveyance efficiency for surface water deliveries (including seepage and evaporation losses) is *CE* (Figure 6-3). The available surface water (Av_S_t) in period *t* is the sum of the available storage in the *r*-eth reservoir supplying the user ($Av\_S_t^r, r = 1, \dots, R$). This is equal to the reservoir initial storage ($S_{t-1}^r, r = 1, \dots, R$) minus any required minimum storage ($S_{min}^r, r = 1, \dots, R$).

$$Av\_S_t = \sum_{r=1}^{R} Av\_S_t^r = \sum_{r=1}^{R} (S_{t-1}^r - S_{min}^r) \qquad \text{Equation 6-2}$$

To track the water deposited in and withdrawn from the groundwater bank, the following three cases are considered:

1. *Available surface water exceeds requirement*

$$Av\_S_t \geq (SW_t + GW_t)/CE \qquad \text{Equation 6-3}$$

In this case, *in lieu* groundwater banking is invoked, curtailing groundwater pumping and providing all water from surface water sources. A deposit of GW_t is credited in the bank.

$$Bank_t = Bank_{t-1} + GW_t \qquad \text{Equation 6-4}$$

2. *Available surface water is more than the surface water demand (plus losses), but less than total demand*

$$SW_t/CE \leq Av\_S_t < (SW_t + GW_t)/CE \qquad \text{Equation 6-5}$$

In this case, water is supplied from both surface and ground water and the bank is unaffected.

$$Bank_t = Bank_{t-1} \qquad \text{Equation 6-6}$$

3. *Available surface water is less than surface water right (plus losses)*

$$Av\_S_t < SW_t/CE \qquad \text{Equation 6-7}$$

In this case, water is supplied from surface water to the extent possible, but there will be a surface water deficit, $Av\_S_t - SW_t < 0$, that must be covered from a combination of groundwater and withdrawals from the bank.

$$Bank_t = Bank_{t-1} - (SW_t - Av\_S_t) \qquad \text{Equation 6-8}$$

Since the 1970's, studies of banking water in the ground have been conducted to determine the economic and hydraulic feasibility for storing water in the ground and recovering it when is needed (NHI, 2001). Since then, groundwater banking projects have been implemented in areas where the water resources are stressed. Successful groundwater banking programs of include the Semitropic Groundwater Banking project (SWSD, 2004), the Kern Water Bank (KWBA, 2008) and the Arvin Edison Water Storage District (NHI, 2001) in the state of California. In all these cases, the groundwater bankers are irrigation districts with groundwater rights; the programs are supported by external clients, such as the Metropolitan Water District of Southern California; and they involve the storage of clients' surplus of water in wet years in the local aquifers and water recovery and delivery in dry years. The development of groundwater banks includes the assessment of hydrogeology and water quality, legal and financial issues, monitoring programs, third party impacts, as well as proper water planning and management of the aquifers. An important key aspect for the success is the efficient communication among the committees that organize the groundwater banks and the groundwater bankers, who are the owners of the groundwater rights. Unsuccessful programs of groundwater banking have failed in one or several of the previous characteristics mentioned (NHI, 2001). At the beginning of the operation of the Drought Water Bank in Butte County, California, the program was unsuccessful because third parties were affected during the recovery of banked water. Pumping rules were modified to correct this. The program still operates with successful results (Coppock and Kreith 1992; WWD 2004).

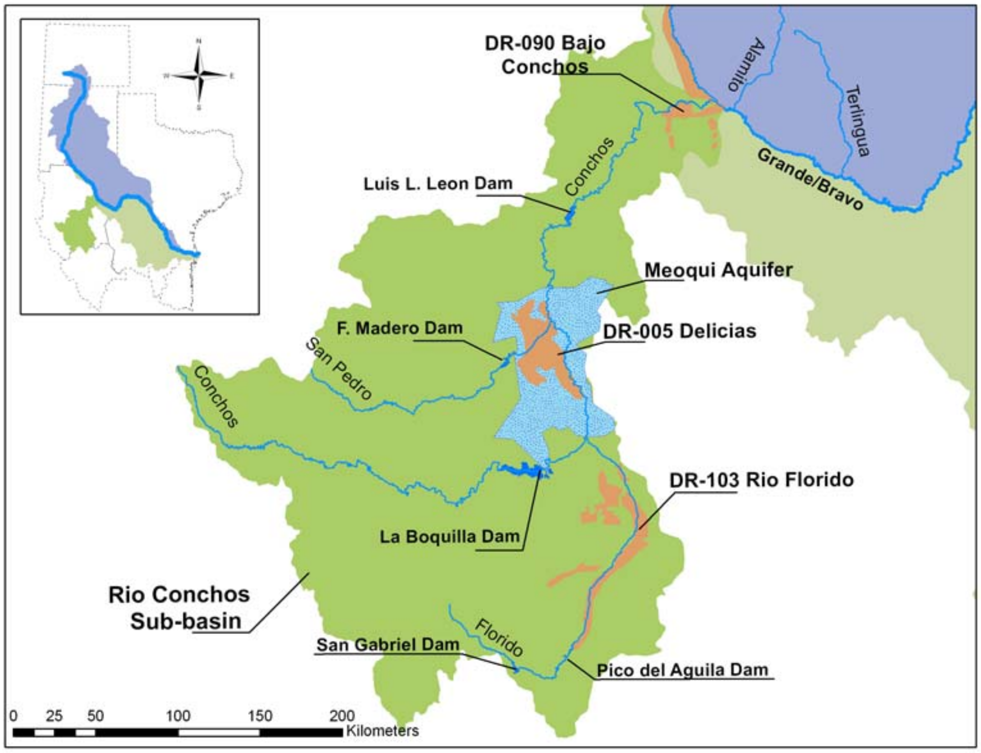


Figure 6-4: Groundwater banking in the Rio Conchos Basin

Irrigation district 005 Delicias (DR-005) is located in the Rio Conchos basin, a sub-basin in the middle part of the Rio Grande/Rio Bravo basin (see Figure 6-4). DR-005 has a combined surface and ground water concession of 1130.546 million m^3 and it is supplied by two sources, 189 million m^3/year from groundwater out of the Meoqui aquifer and 941 million m^3/year from surface water via the La Boquilla and Francisco I. Madero reservoirs (744 and 197 million m^3/year, respectively). The conveyance efficiency of delivering surface water is estimated to be 80% (Collado, 2002); no conveyance loss is assumed for delivering groundwater, it is considered that wells are uniformly distributed along the irrigation district. Further research is needed to determine conveyance losses from groundwater extraction. Thus, the threshold of available storage that controls deposits to the groundwater bank is $(SW_t + GW_t)/CE$ =1,409 million m^3

and the threshold to control withdrawals from the bank is $SW_t/CE = 1{,}173$ million m^3. For DR-005, the available surface water in the system is the sum of the available storage in Francisco I. Madero and La Boquilla reservoirs. The minimum operating storages for La Boquilla and F. I. Madero reservoirs are 165 and 8.5 million m^3, respectively. The present research does not estimate the investment to implement a groundwater banking in DR-005 Delicias, further research is needed to determine this investment.

In order to be initiated and implemented the groundwater banking, policy, institutional and legal changes are necessary to encourage its creation. According to the National's Waters Law of Mexico, water in the bank would belong to CONAGUA (2008.a). An agreement between CONAGUA and DR-005 Delicias could be undertaken to implement the groundwater bank. The DR-005 water users would seek permission from CONAGUA to temporarily interrupt groundwater deliveries and, in exchange, use surface water, while CONAGUA must ensure the return of the groundwater to the users in case of drought. The possibility of obtaining an extra amount of water from the bank during drought periods may encourage groundwater users to switch to this method. For the *In Lieu* groundwater banking policy, this research focuses on the physical feasibility of the overall management policy, this research does not investigate political, institutional or legal challenges of implementing a groundwater bank or the details of the hydraulic conditions that may be encountered in the Meoqui aquifer as a result of bank operations; further research is needed in these area.

6.2.5 Environmental Flows

Due to high water demand, the scarcity of water resources, and the complexity of water allocation in the Rio Grande/Rio Bravo basin, environmental flows have not been considered as an integral part of the water management in this basin. Important environmental habitats such as the Big Bend National and State Parks in the U.S., the Northern Chihuahuan desert, Maderas del Carmen, Ocampo and Cañón de Santa Elena natural reserves in Mexico are ecologically threatened because of the lack of environmental water management policies. Historically, the Rio Grande/Rio Bravo basin has been manipulated in an exclusive human water resource management (Enriquez-Coyro, 1976), not considering the environmental needs for the native ecosystems. One of the policies proposed in this research is to find alternative water management policy that delivers environmental flows without worsening the water supply of other users in the basin; the environmental flows calculated for the Rio Conchos are used for this purpose.

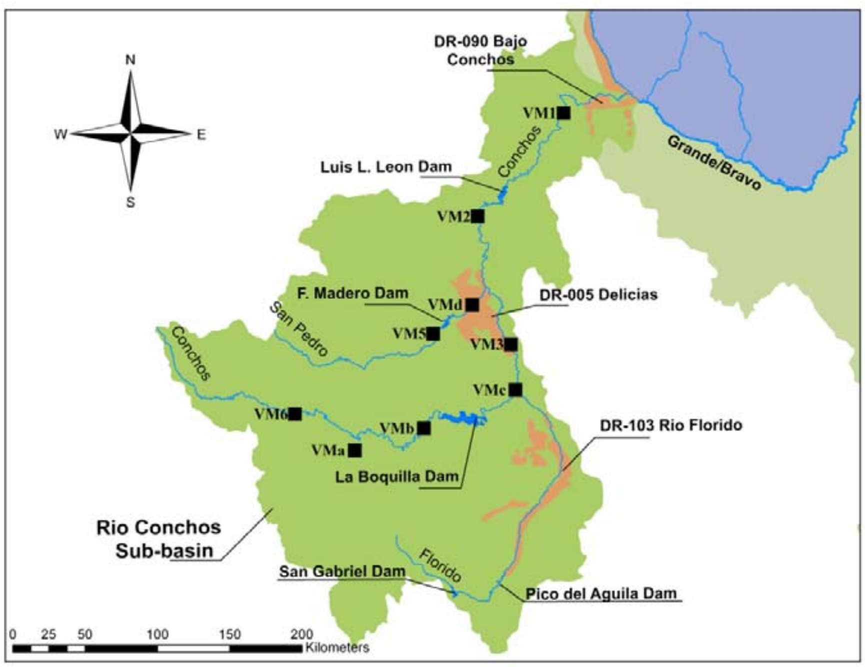


Figure 6-5: Environmental Control Points in the Rio Conchos Sub-basin

As part of an environmental flow assessment, the World Wildlife Fund made significant efforts to estimate the environmental flows required to preserve the health of riparian ecosystems in the Rio Conchos sub-basin. The process began in 2006 with a workshop of the Building Block Methodology (WWF 2006) and concluded in 2008 with estimation of the environmental flows for 9 locations along the Rio Conchos basin (WWF 2008). Figure 6-5 shows the locations where the environmental flows were determined. The geomorphology, flora and fauna (fish and invertebrates) were considered to determine the flows necessary to meet the environmental requirements (Tharme and King 1998). Daily environmental flows for maintenance and drought conditions were estimated for each control point. In this research, daily flows were aggregated into monthly values to be declared into the Rio Grande/Bravo WEAP model; thus, monthly environmental requirements for drought and maintenance conditions were loaded into the model. Table 6-6 shows the name, stream and annual volume required for each location.

Table 6-6: Environmental Flows in the Rio Conchos Basin

			Environmental Flow	
			Maintenance	Drought
Site	Name	River	(1X10^6 m^3/year)	(1X10^6 m^3/year)
VM1	Cuchillo Parado	Conchos	381.5	47.7
VM2	El Potrero	Conchos	323.6	36.2
VM3	Estación Conchos	Conchos	27.1	14.2
VM5	San Pedro de Conchos	San Pedro	114.2	34.1
VM6	Agua Caliente	Conchos	134.5	24.4
VMa	Valle del Rosario	Balleza	548.1	236.3
VMb	Valle de Zaragoza	Conchos	1214.8	576.6
VMc	Camargo	Conchos	50.6	23.6
VMd	C. Ortíz	San Pedro	60.8	45.3

In order to evaluate the hydrologic feasibility of environmental flows in the Rio Conchos basin, the following methodology has been developed:

1. An evaluation of the environmental flows proposed with the actual water management policies is done to identify conflict points where environmental requirements are more threatened.
2. An alternative operation policy is proposed.
3. The alternative operation policy is evaluated to determine if it improves the environmental requirements and how much this policy affects or benefits other water users in the basin.

Results from the no policy scenario (*Baseline* scenario, Chapter 8 Results by User: Environment) showed that, in recent years, the environmental requirements have not been met in any of the control points (Sandoval-Solis and McKinney 2009). Furthermore, results also showed that the critical points are VMc Camargo and VMd. C. Ortiz. These control points are located just downstream La Boquilla and Francisco I. Madero dams, respectively. Because of their location an alternative water management policy is proposed below. An analysis of La Boquilla–Francisco I. Madero reservoir system was done to decide what kind of environmental flows, maintenance or drought, needs to be allocated each year to control points VMc and VMd. At the beginning of each hydrological year, the available surface water in the system Av_S_t is estimated through Equation 6-2. In parallel, the annual $Diversion$ required to satisfy the i-eth water users from this reservoir system is estimated, dividing the annual surface water demand ($\sum_{t=1}^{t=12} SW_t^i$) by the conveyance losses (CE), as shown in Equation 6-9.

$$Diversion = \sum_{t=1}^{t=12} SW_t^i / CE \qquad \text{Equation 6-9}$$

If the Groundwater banking policy is implemented jointly with the environmental flows, the $Diversion$ is expressed as

$$Diversion = \sum_{t=1}^{t=12}\left(SW_t^i + GW_t^i\right)/CE \qquad \text{Equation 6-10}$$

Finally, the available storage Av_S_t is compared with the $Diversion$. Based on this comparison a decision is made:

- ❖ If the *available storage* is larger than the required *diversion*, the maintenance flow level is assigned for the environmental flow Q in that year.

$$\text{If } Av\_S_t > Diversion \;\rightarrow\; Q_{Maintenance}^{Control\ point\ i} \qquad \text{Equation 6-11}$$

- ❖ If the *available storage* is less than the required *diversion*, the drought flow is assigned for the environmental flow in that year.

$$\text{If } Av\_S_t < Diversion \;\rightarrow\; Q_{Drought}^{Control\ point\ i} \qquad \text{Equation 6-12}$$

The philosophy of this policy is the following: if the water users are expecting a shortage in their water supply, it is reasonable to ask only for the minimum volume of water for the environment, i.e., the drought flow; on the contrary, if there is enough water in the reservoir system to supply the water users dependent on this reservoir system, it is reasonable to ask for the normal flow for the environment, i.e., the maintenance flow. In this policy is proposed an annual decision to choose whether to provide drought or maintenance flow; thus environmental monthly flows depend on annual decisions. In order to estimate a cost of this policy, let's consider that the environmental flows are obtained through buying back water rights, such as in the PADUA program. The present cost for buying back 1,000 m^3 of surface water rights is $217.47, as estimated in Chapter 6.2.1 ($2,740 pesos per 1,000 m^3, monetary exchange 12.6 pesos per dollar). In this policy, it is necessary to buy 111.4 million m^3 of surface water under normal conditions, 50.6 million m^3 for VMc Camargo and 60.8 million m^3 for VMd C. Ortiz. Thus, the cost to buy 111.4 million m^3 of surface water is $24.2 million ($305.2 million pesos, monetary exchange 12.6 pesos per dollar). If the water saved through Minute 309 is delivered in an environmental pattern, there is no cost for this policy.

6.3 Lower basin: the Lower Rio Grande Valley

For the middle and lower Rio Grande Valley the reduction in the water allocation for U.S. water user along the thirteen Water Master Sections is a policy already implemented in this region; two policies are proposed in this research, the buyback of water rights and the improvement in the infrastructure in irrigation district 025 Bajo Rio Bravo.

6.3.1 Reduction in water allocation for the Water Master Sections

Below the international reservoir Amistad, water in the U.S. is allocated according to the Texas Rio Grande Watermaster Program (TCEQ 2006). In this program the stream of the Rio Grande/Rio Bravo has been divided in two regions: the Middle Rio Grande and the Lower Rio Grande Valley (Figure 6-6). The middle Rio Grande, which is the region between Amistad and Falcon dams, is divided in 6 reaches; and the Lower Rio Grande Valley, which is the region from Falcon dam downstream to the Gulf of Mexico, is divided in 7 reaches. Thus, for operational purposes the TCEQ divided the Rio

Grande/Rio Bravo in 13 reaches. In this research Watermaster Section (WMS) reaches 1 to 6 are referred to the ones located in the middle Rio Grande and reaches 7 to 13 are referred to the ones located in the Lower Rio Grande Valley, as shown in Figure 6-6.

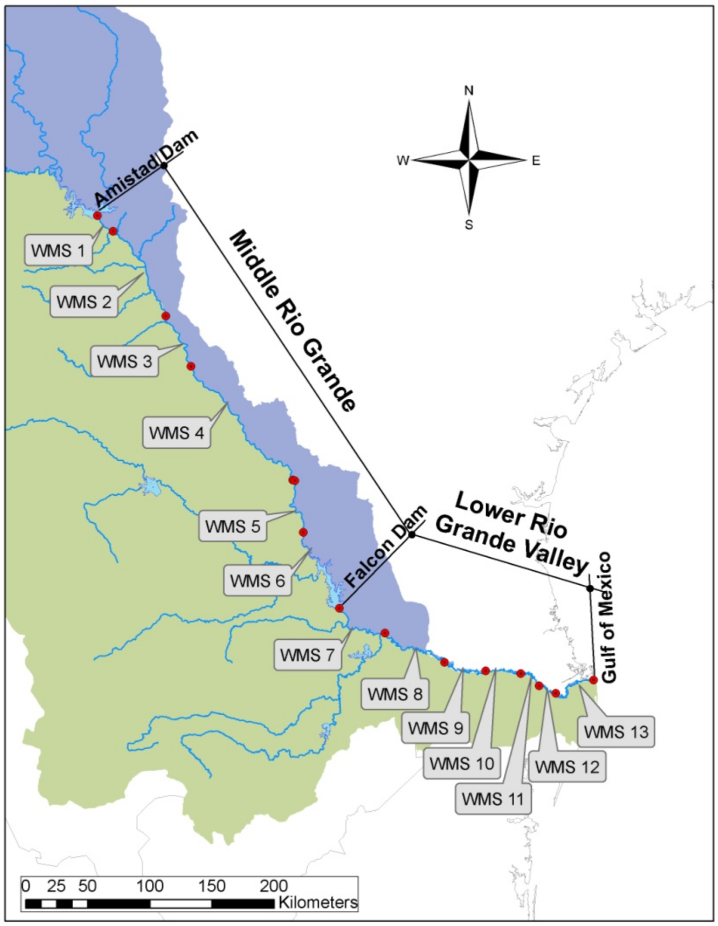


Figure 6-6: TCEQ Water Master Sections

During the last drought (1994-2004) the water supply for the U.S. was compromised. At the beginning of the drought (1994-1996) the water supply for the Watermaster Section 8 to 13 agriculture use Type A (WMS 8-13) was on average 78% (1400 million m^3/year – 1’135,000 acre-feet/year) of the full allocation demand (1801 million m^3/year – 1'460,000 acre-feet/year). For the rest of the drought (1997-2004), the water supply was on average 53% (950 million m^3/year – 770,000 acre-feet/year) of the full allocation demand (IBWC 2009). This uncertainty in the water supply provoked the 75th Texas Legislature to order a study (Brandes 2004) that defined the water availability and the water use limits and vulnerabilities of the system (TWDB 2001). As a result, the "Current Allocation" for U.S. water users other than municipal, domestic and industrial was set at 70% of the full allocation demand (TCEQ 2007). The current allocation has been further reduced to 62% of the full allocation demand (personal communication, Carlos Rubenstein, Commissioner, TCEQ, October 2009). In this research is evaluated this reduction in the water allocation, no investment is associated with these water management policy.

6.3.2 Buy Back of Water Rights in DR-025 Bajo Rio Bravo

As a proposed policy, in this research is evaluated the hypothetical scenario that water rights are bought back in DR-025 Bajo Rio Bravo, located in the Lower Rio Grande Valley (see Figure 6-7). Data from DR-005 Delicias is used as a reference to propose the volume of water rights bought back and the investment required in DR-025 Bajo Rio Bravo. Considering that the volume of surface water rights bought back in DR-005 Delicias is 91.3 million m^3/year (74,000 acre-feet/year), for DR-025 Bajo Rio Bravo is proposed a volume of 100 million m^3/year (81,000 acre-feet/year) of surface water rights bought back. As shown in Table 6-2 of Chapter 6.2.1, the cost per million of water saved is \$0.217 million for DR-005 Delicias in 2011, considering an annual interest rate of 6.5% from 2006 to 2011 (\$2,740 pesos per thousand cubic meters; monetary exchange \$12.6 pesos per dollar). Consequently, for the proposed volume of 100 million m^3 of surface water rights to be bought back in DR-025 Bajo Rio Bravo at a cost of $0.217 per million cubic meters saved, the total investment required to implement this policy is $21.7 million, ($274 million pesos, monetary exchange $12.6 pesos per dollar), see Table 6-7.

Table 6-7: Estimated investment to buy-back of water rights for DR-025 Bajo Rio Bravo

Irrigation District	Surface Water Buy-Back ($1X10^6$ m^3/year)	Cost per million of water bought-back ($ Million)*	Investment ($ Million)
025 Bajo Rio Bravo	100	0.217	21.7

* $217 per 1,000 m^3 of surface water bought back ($2,740 pesos); annual interest rate 6.5%; monetary exchange 12.6 pesos per dollar. Cost derived in Chapter 6.2.1, Table 6-2

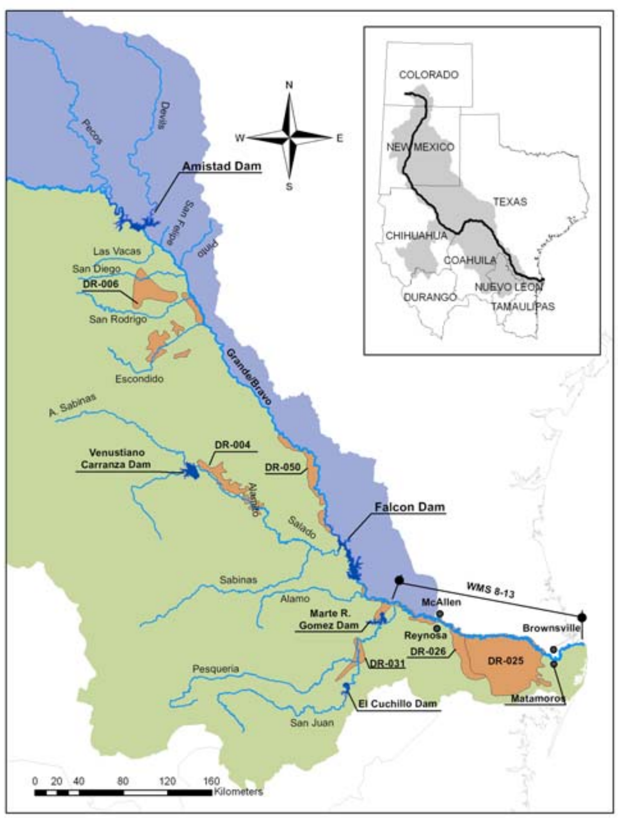


Figure 6-7: Lower Rio Grande Valley

The proposed volume of water rights to be bought back (100 million m^3/year - 81,000 acre-feet/year) is reasonable since in DR-005 Delicias a similar amount of surface water rights has already been bought back. In addition, Zatarain et al (2005) estimated that about 14% of the irrigated area in DR-025 Bajo Rio Bravo is susceptible to salinity problems, and thus this area is susceptible to be bought back from the irrigation district. Legally, this scenario is feasible because the rules of the PADUA program considered as possible recipients of this program, users with water rights from DR-025 Bajo Rio Bravo (SAGARPA 2003).

6.3.3 Improvement in Infrastructure at DR-025 Bajo Rio Bravo

As a proposed policy, in this research is evaluated the improvement in the infrastructure of irrigation district DR-025 Bajo Rio Bravo. Data from DR-005 Delicias is used as a reference to propose the increase in conveyance, application and global efficiencies for DR-025 Bajo Rio Bravo. According to minute 309, the global efficiency for DR-005 increased 22% (from 33% to 55%) and the application efficiency increased 26% (from 54% to 80%) (IBWC 2003). These increments in the application and global efficiencies are used to estimate a similar improvement in the infrastructure of DR-025 Bajo Rio Bravo. Table 6-8 shows that the volume of water saved is 427 million m^3/year (346,000 acre-feet/year) due to an increase in the global efficiency of 22% (from 39% to 61%), in the application efficiency of 26% (from 54% to 80%) and in the conveyance efficiency of 4% (from 73% to 77%); considering that the actual extraction of DR-025 from Falcon dam is estimated as 1184 million m^3/year (960,000 acre-feet/year) (Collado 2002). Equation 6-1 is used to determine the conveyance efficiency given the global and application efficiencies.

Table 6-8: Proposed improvements in the conveyance, application and global efficiencies for DR-025 Bajo Rio Bravo

Extraction Volume ($1X10^6$ m^3/year)	Conveyance Efficiency (%)	Application Volume ($1X10^6$ m^3/year)	Application Efficiency (%)	Consumed Use ($1X10^6$ m^3/year)	Global Efficiency (%)
1184	73%	860.54	54%	464.69	39%
757	77%	580.87	80%	464.69	61%
427	**Water Saved**				

Similar actions as the ones executed in DR-005 Delicias must be applied in DR-025 Bajo Rio Bravo to achieve this increment in the global efficiency, such as reducing the conveyance losses by lining main and lateral canals and increasing the application efficiency on the farms by installing low pressure supply systems, land leveling, and implementing sprinkler systems, among others actions.

Table 6-9: Investment to improve the infrastructure in DR-005 Delicias

Irrigation District	Water Saved ($1X10^6$ m^3/year)	Cost per million of water saved ($ Million)*	Investment ($ Million)
025 Bajo Rio Bravo	427	0.489	209

* Investment in DR-005 Delicias in 2004: $108 million; water saved: 343 million m^3. Considering a 6.5% annual interest rate; investment in 2011: $168 million. Cost per million of water saved: $0.489 million ($168 million / 343 million m^3 of water saved); monetary exchange 12.6 pesos per dollar. Cost derived in Chapter 6.2.3, Table 6-5

In order to estimate the investment needed to implement these measures in DR-025 Bajo Rio Bravo, data from DR-005 Delicias is used. The estimated cost per million of water saved in DR-005 Delicias in present value is $0.489 million ($6.2 million pesos per million of water saved, monetary exchange 12.6 pesos per dollar) (see Chapter 6.2.3: Table 6-5). This value is used as a guide to estimate the investment for this policy. Thus, if the water expected to be saved in DR-025 Bajo Rio Bravo is 427 million m^3/year, the investment necessary to save this amount of water is $196.0 Million dollars ($2,470 million pesos of investment, monetary exchange 12.6 pesos per dollar) (Table 6-9).

This scenario is evaluated in two variations: (1) considering that the investment is fully provided by Mexico, in which case, the water saving are used by DR-025 Bajo Rio Bravo and (2) considering that half of the investment is provided by the U.S. and half by Mexico, in which case the water savings are divided between DR-025 Bajo Rio Bravo and Water Master Section 8 to 13 (WMS 8-13).

6.4 CURRENT SCENARIO

The Current scenario considers the policies that have been implemented in the basin, since 2004. Three policies have been already implemented:

a) The buyback of water rights through the PADUA program,
b) The improvement in the infrastructure due to IBWC Minute 309, and
c) The reduction in the water allocation for Water Master Sections' users in the U.S.

The Current scenario represents the system as it is actually working.

Chapter 7 Scenarios Results

This chapter presents the results of the scenarios described in Chapter 6 using the methodology proposed in Chapter 3 and 4 with the water resources planning model described in Chapter 5. First, an initial set of scenarios is listed and briefly described. These scenarios are the policies presented in Chapter 6 or basic combinations of these. Second, results from these basic scenarios are shown. An analysis of the results is done to identify the benefits and worsening that each scenario represent to the system. Third, from the previous analysis a set of winner scenarios is identified in order to define the "Meta-scenarios", which are scenarios integrated of policies that promote benefits to the water resources system.

7.1 SCENARIOS

The scenarios evaluated in this research are listed in Table 7-1. The results from these scenarios are analyzed in order to identify the benefits or worsening they represent to the system. Some basic combinations are also analyzed to evaluate their results working together. Results from the upper and lower basin (LRGV – Lower Rio Grande Valley) scenarios help us identify which combinations may lead us to winner scenarios called "Meta-scenarios".

Table 7-1: List of scenarios for the Rio Grande/Rio Bravo Basin

Scenario	Description
Baseline	Water management before any policy was implemented (<2004). For the **U.S.** water rights are **70%** of the full allocation demand and for **Mexico** is the **demand** in **2004**.
I	**Buy Back** of water rights according to the **PADUA program**. Reduction of the water demand in DR-005 Delicias and DR-090 Bajo Rio Conchos due to the buyback of water rights.
II	**Groundwater Banking** in DR-005 Delicias. Conjunctive use of surface water and groundwater to supply the water demand for DR-005 Delicias.
I + II	**Buy Back of water rights plus groundwater banking** in DR-005 Delicias. Evaluation of these policies working together in DR-005.
III	**Improvement in infrastructure** due to **Minute 309** in DR-005 Delicias. Improvement in the conveyance and application efficiencies due to the measures proposed in Minute 309. **The water savings are conveyed to the Rio Grande/Rio Bravo each December and January**.
IV	**Environmental flows in the Rio Conchos** Sub Basin. Intentional delivery of water from La Boquilla and Francisco I. Madero reservoirs to meet environmental requirements.
III + IV	**Improvement in infrastructure** due to **Minute 309** in DR-005 Delicias **plus** the **delivery of the water savings in an environmental pattern**.
I (LRGV)	**Buy Back** of water rights in **DR-025 Bajo Rio Bravo** who is located in the Lower Rio Grande Valley (LRGV).
III (LRGV)	**Improvement in the infrastructure** in **DR-025 Bajo Rio Bravo**. Improvement in the conveyance and application efficiencies of DR-025.
I + III (LRGV)	**Buy Back** of water rights **plus improvement in the infrastructure** of **DR-025 Bajo Rio Bravo.**
III (LRGV) Shared	**Improvement in the infrastructure** in **DR-025 Bajo Rio Bravo and sharing of the savings with WMS 8-13.** This policy considers that both irrigation districts made the investment for the improvements and thus, share the water saved.
V(LRGV)	**Reduction** in the **water demand** of **WMS 8-13 from 70% to 62%** of the full allocation demand.

7.1.2 Results by User

This section presents the results for selected water users that are considered relevant in the basin: (a) DR-005 Delicias, the biggest water user in Mexico; (b) DR-025 Bajo Rio Bravo, the biggest water user of Mexico in the Lower Rio Grande Valley; (c) Water Master Section 8-13 Agriculture use A (WMS 8-13), the biggest water users in the U.S; (d) Treaty Obligations, the delivery of water from Mexico to the U.S. according to the 1944 Treaty; and (e) environmental control point VMc Camargo, control point located below La Boquilla reservoir whose environmental flows have the worst performance in the baseline scenario.

7.1.2.1 DR-005 Delicias

Irrigation District DR-005 Delicias has a combined surface and ground water concession of 1,131 million m^3 and it is supplied by two sources, 189 million m^3/year from groundwater out of the Meoqui aquifer and 942 million m^3/year from surface water via La Boquilla and Francisco I. Madero reservoirs (744 and 197 million m^3/year, respectively). Table 7-2 shows the sustainability index results for total, surface and groundwater demands. Results for the LRGV scenarios are not presented for brevity reasons since these results do no change with respect of the *Baseline* scenario. Figure 7-1 shows the sustainability index and the differences "Δ(Criteria)" of the performance criteria considered for this water user with respect of the *Baseline* scenario: Reliability, Resilience, 1-Vulnerability and 1-Max. Deficit. These Δ's help identify which performance criteria improve due to the policy implemented.

Results show that the buyback of water rights through the PADUA program (I) and the groundwater banking (II) improve the water management for DR-005 Delicias. The combination of the previous two policies (I+II) provides the best results for this water user. Also, results show that the improvement in infrastructure (III) and the delivery of environmental flows (IV) from La Boquilla and Francisco I. Madero reservoirs worse its water management.

Table 7-2: Sustainability Index for DR-005 Delicias, Baseline and Scenarios

	Total		Surface Water		Groundwater	
	Demand	Sust.	Demand	Sust.	Demand	Sust.
Scenario	($1X10^6$ m^3/year)	(%)	($1X10^6$ m^3/year)	(%)	($1X10^6$ m^3/year)	(%)
Baseline	*1130.5*	*21*	*941.6*	*16*	*189.0*	*35*
I	1021.0	24	850.3	18	170.6	38
II	1130.5	24	941.6	18	189.0	39
I + II	**1021.0**	**25**	**850.3**	**20**	**170.6**	**39**
III	855.5	9	666.5	30	189.0	1
IV	1130.5	20	941.6	15	189.0	34
III + IV	855.5	6	666.5	15	189.0	0

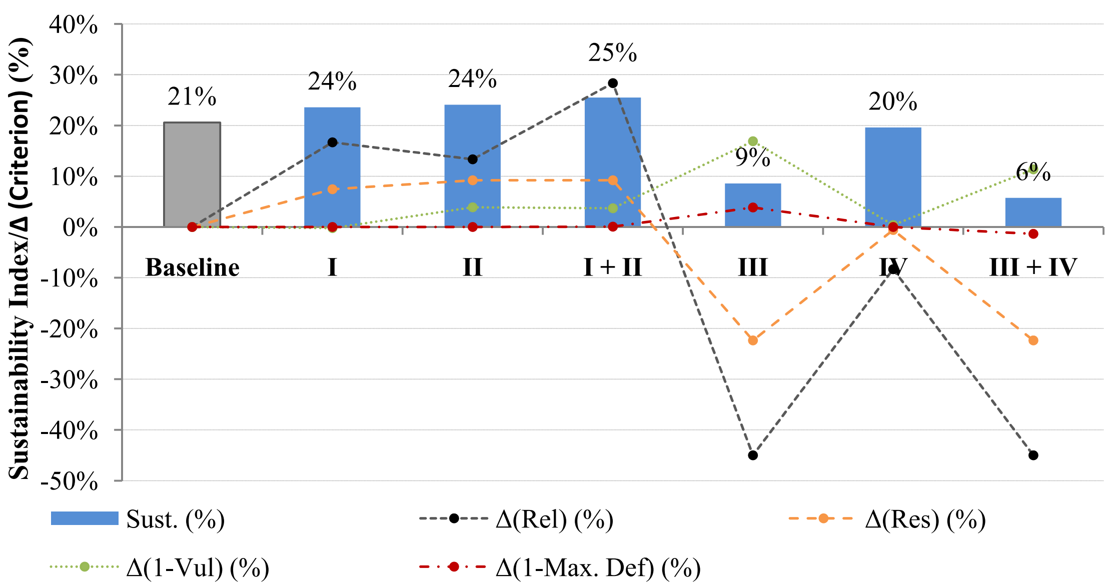


Figure 7-1: Sustainability Index and Δ(Criterion) of DR-005 Delicias

7.1.2.2 DR-025 Bajo Rio Bravo

Irrigation district DR-025 Bajo Rio Bravo has water concession of 861 million m^3/year supplied from surface water of Falcon reservoir. Table 7-3 shows the sustainability index results for this water user. Results for all scenarios are shown because it is located in the lower part of the basin and any change in the water allocation policy impacts its water supply. Figure 7-2 shows the sustainability index and the differences (Δ's) of the performance criteria considered for this water user with respect of the *Baseline* scenario: Reliability, Resilience, 1-Vulnerability and 1-Max. Deficit.

For upper basin scenarios, results show that none of the scenario harms the water management for DR-025. Three scenarios in the upper basin benefits DR-025: (1) the buyback of water rights due to the PADUA program (I), (2) the combination of the PADUA program and the groundwater banking (I+II) , and (3) Minute 309 plus the delivery of the savings in an environmental pattern (III+IV).

For lower basin scenarios, all the scenarios improve the water supply for DR-025. In any of the cases were improvements in the infrastructure is considered (III(LRGV), I+III(LRGV) and III(LRGV) Shared), the water supply improves. Notice that as a side effect of the reduction of the water demand in WMS 8-13 (V), DR-025 is slightly benefited from this policy. Also, the buyback of water rights in DR-025 (I(LRGV)) improves its water supply.

Table 7-3: Sustainability Index for DR-025 Bajo Rio Bravo, Baseline and Scenarios

Scenario	Demand ($1X10^6$ m^3/year)	Sustainability Index (%)
Baseline	*861*	*48%*
I	861	52%
II	861	49%
I + II	861	52%
III	861	50%
IV	861	50%
III + IV	861	52%
I (LRGV)	761	52%
III (LRGV)	581	71%
I + III (LRGV)	**514**	**100%**
III (LRGV) Shared	581	52%
V(LRGV)	861	49%

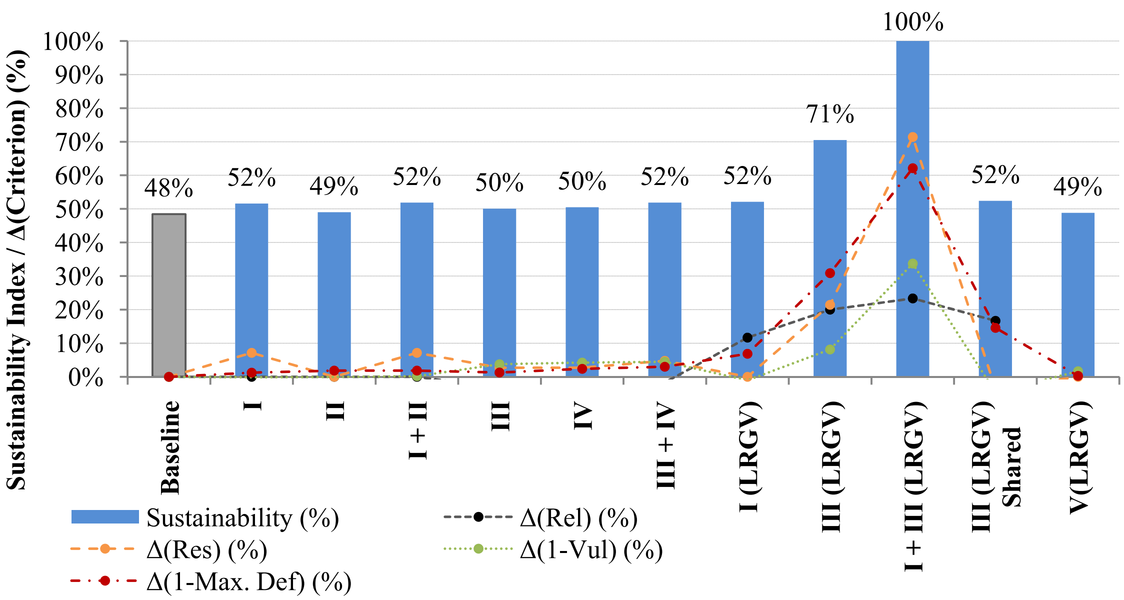


Figure 7-2: Sustainability Index and Δ(Criterion) of DR-025 Bajo Rio Bravo

7.1.2.3 Water Master Section 8-13

Irrigation districts Water Master Section 8 to 13 Agriculture A (WMS 8-13) has full allocation demand of 1801 million m^3/year and it is supplied from surface water of Falcon reservoir. In 2002, according to the TCEQ (TCEQ 2007), the current allocation demand was set to 70% of the full allocation demand, 1261 million m^3/year. This percentage is used in the *Baseline* scenario. Table 7-4 shows the sustainability index results for its water demand. Similarly to DR-025, results for all scenarios are shown because this water user is located in the lower part of the basin and any change in the water allocation policy impacts its water supply. Figure 7-3 shows the sustainability index and the differences (Δ's) with respect of the *Baseline* scenario.

For upper basin scenarios, results show the buyback of water rights through the PADUA (I) program and the improvement in infrastructure due to Minute 309 (III) affect the water management for WMS 8-13. The rest of the scenarios on the upper basin do not harm or improve the water management for this user. In fact, two scenarios in the upper basin improves its water management: the PADUA program plus the groundwater banking (I+II) and Minute 309 delivering the saving in an environmental pattern (III+IV).

For lower basin scenarios, all of them improve the water supply for WMS 8-13. All the scenarios promoting a more conservative and sustainable water management in DR-025 Bajo Rio Bravo improved the water supply for WMS 8-13 (I(LRGV), III(LRGV), I+III(LRGV) and III(LRGV)Shared). The scenario that provides most benefits is the improvement in the infrastructure of DR-025 and sharing the water saved.

Table 7-4: Sustainability Index for WMS 8-13, Baseline and Scenarios

Scenario	Demand ($1X10^6$ m^3/year)	Sustainability Index (%)
Baseline	*1261*	*32%*
I	1261	30%
II	1261	33%
I + II	1261	35%
III	1261	29%
IV	1261	32%
III + IV	1261	35%
I (LRGV)	1261	35%
III (LRGV)	1261	40%
I + III (LRGV)	1261	39%
III (LRGV) Shared	1261	41%
V(LRGV)	1117	39%

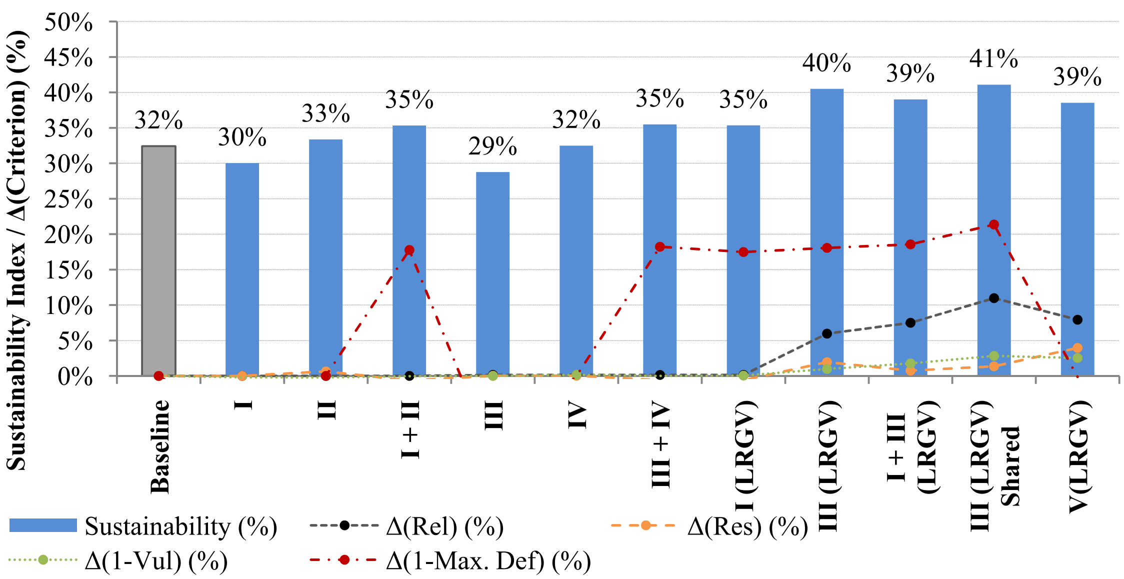


Figure 7-3: Sustainability Index and Δ(Criterion) of WMS 8-13

7.1.2.4 Treaty Obligations

According to 1944 Treaty, Mexico has to deliver 431.721 million m^3/year as an average over cycles of 5 consecutive years from one third of the water reaching the Rio Grande/Rio Bravo of 6 Mexican tributaries: Conchos, Las Vacas, San Diego, San Rodrigo, Escondido and Salado. The treaty cycles can expire in less than five years if the U.S. storage in both dams is filled with water belonging to the United States.

Table 7-5 shows the sustainability index results for the Treaty Obligations. Results are presented for all scenarios because any change in the water management of the basin affects the meeting of this international agreement. Figure 7-4 shows the sustainability index and the differences (Δ's) of the performance criteria considered for this water user with respect of the *Baseline* scenario: Reliability, Resilience, 1-Vulnerability and 1-Std. Deviation.

None of the scenarios, neither in the upper nor the lower basin, affect the delivery of the treaty obligations. For upper basin scenarios, Minute 309 scenarios promoting the improvement in infrastructure (III and III+IV) benefit the most the treaty obligations.

For lower basin scenarios, also the scenarios related with the improvement of infrastructure (III(LRGV) and III(LRGV)Shared), in this case of DR-025 Bajo Rio Bravo, promote benefits for the treaty obligations. Also the reduction in the water demand of WMS 8-13 (V(LRGV)) improves the water management of the treaty obligations which means that the treaty obligations are not only function of the water delivered from Mexico to the U.S. but also to the water use in the U.S.

Table 7-5: Sustainability Index for Treaty Obligations, Baseline and Scenarios

Scenario	Demand ($1X10^6$ m^3/Cycler)	Sustainability Index (%)
Baseline	*2159*	*51%*
I	2159	58%
II	2159	52%
I + II	2159	63%
III	2159	69%
IV	2159	52%
III + IV	2159	64%
I (LRGV)	2159	51%
III (LRGV)	2159	58%
I + III (LRGV)	2159	51%
III (LRGV) Shared	2159	66%
V(LRGV)	2159	59%

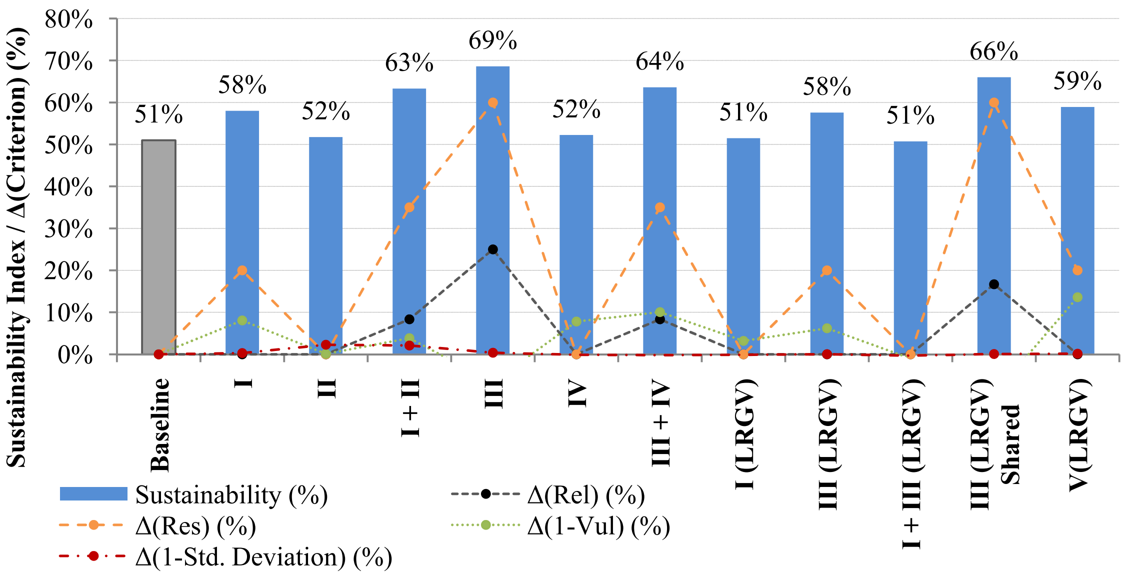


Figure 7-4: Sustainability Index and Δ(Criterion) of Treaty Obligations

7.1.2.5 Environment

The environmental flows for 9 control points located in the Rio Conchos basin has been defined using the Building Block method (Chapter 6: Water Management scenarios, Upper basin:: Environmental flows) (WWF 2006). Here, for purpose of brevity, only results from control point VMc Camargo are presented (Table 7-6 and Figure 7-5) because this point has the worst performance of all control points in the *Baseline* scenario. This control point is used to exemplify the use of the sustainability index for environmental requirements. Results for the LRGV scenarios are not presented because they are the same as the *Baseline* scenario results.

Results show that scenarios related with Minute 309 (III and III+IV) and with the delivery of water to the environment (IV) benefit the environmental requirements for VMc Camargo. Specifically, scenario III+IV which delivers the water savings of Minute 309 in an environmental pattern provides the largest benefits to the environment. In this scenario the timing of the water savings' delivery is modified to provide benefits to the environment. Also notice that the scenarios related to buyback of water rights and groundwater banking worse the environmental water supply. Results for the rest of the control points are similar to VMc.

Table 7-6: Sustainability Index for environmental control point VMc Camargo, Baseline and Scenarios

Scenario	Demand ($1X10^6$ m^3/year)	Sustainability Index (%)
Baseline	*23*	*24%*
I	23	22%
II	23	22%
I + II	23	21%
III	23	39%
IV	23	79%
III + IV	23	88%

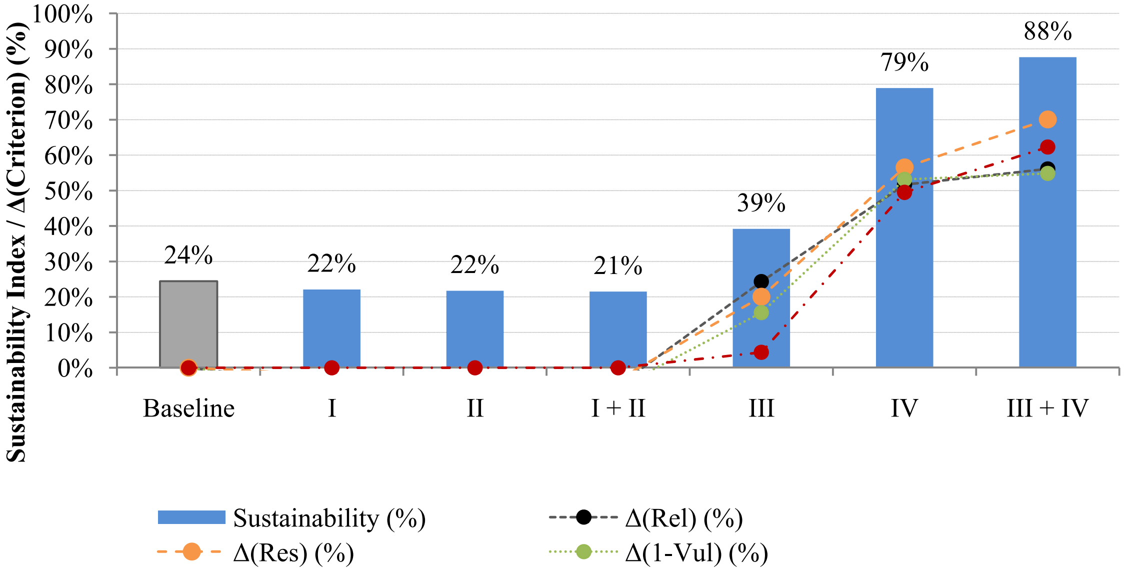


Figure 7-5: Sustainability Index and Δ(Criterion) of environmental control point VMc Camargo

7.1.3 Results by Group

The relative sustainability index (Equation 3-15) is used to summarize the results for water users in the basin. Four groups of interest have been identified in the Rio Grande/Rio Bravo basin:

1. *Rio Grande/Rio Bravo* –includes all water users in the basin: U.S. and Mexican anthropogenic water users, treaty obligations and environmental requirements;
2. *United States* – includes all water users in the U.S.;
3. *Mexico* - includes Mexican water users and the treaty obligations; and
4. *Environment* – includes the environmental requirements in the Conchos basin

7.1.3.1 Rio Grande/Rio Bravo

The relative sustainability index for all the scenarios analyzed and the Baseline scenario is shown in Figure 7-6. For the upper basin scenarios, two scenarios provide more benefits than any other: (1) buyback of water rights through the PADUA program coupled with groundwater banking in DR-005 Delicias (I+II) and (2) the improvement in infrastructure due to Minute 309 with the delivery of the savings in an environmental pattern (III+IV). These scenarios include two policies already implemented (PADUA and Minute 309) and two policies proposed (groundwater banking and environmental flows). For the lower basin scenarios, all the scenarios related with the improvement in infrastructure of DR-025 Bajo Rio Bravo (III(LRGV), I+III(LRGV) and III(LRGV)Shared) provide benefits to the water management in the basin. In addition, the rest of the scenarios in this part of the basin (I(LRGV) and V(LRGV)) also provide benefits to the water management.

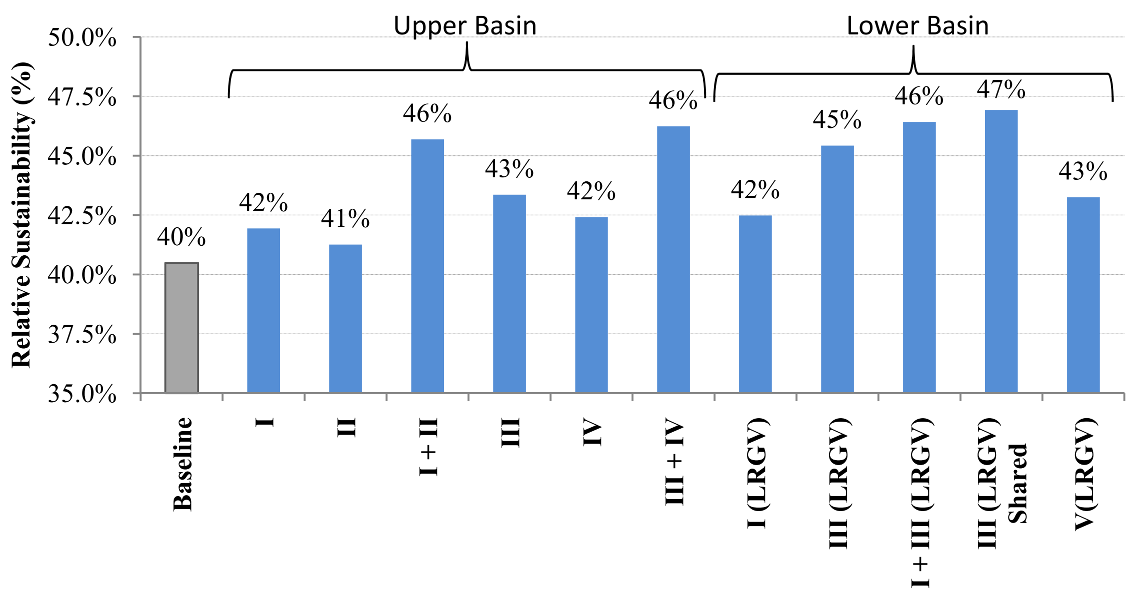


Figure 7-6: Relative Sustainability for the Rio Grande/Rio Bravo

7.1.3.2 United States

Figure 7-7 shows the relative sustainability index for the United States water users' group. For upper basin scenarios, two scenarios provide benefits: (1) buyback of water rights through the PADUA program coupled with groundwater banking in DR-005 Delicias (I+II) and (2) the improvement in infrastructure due to Minute 309 with the delivery of the savings in an environmental pattern (III+IV). A better management in the upper basin leads to more water available in the whole basin for different water users. Notice that the combined policies in the upper basin provides benefits to water users in the U.S. (I+II and III+IV). For lower basin scenarios, all scenarios provide benefits for U.S. water users. The scenarios related with improvement of infrastructure of DR-025 Bajo Rio Bravo (III(LRGV), I+III(LRGV) and III(LRGV)Shared) provide the most benefits for U.S. water users. This is because more water is stored in the international reservoirs, Mexican storage capacity fills more frequently and during spilling, all the inputs are accounted to the U.S. and all the spills accounted to Mexico, according to the provisions of the 1944 treaty.

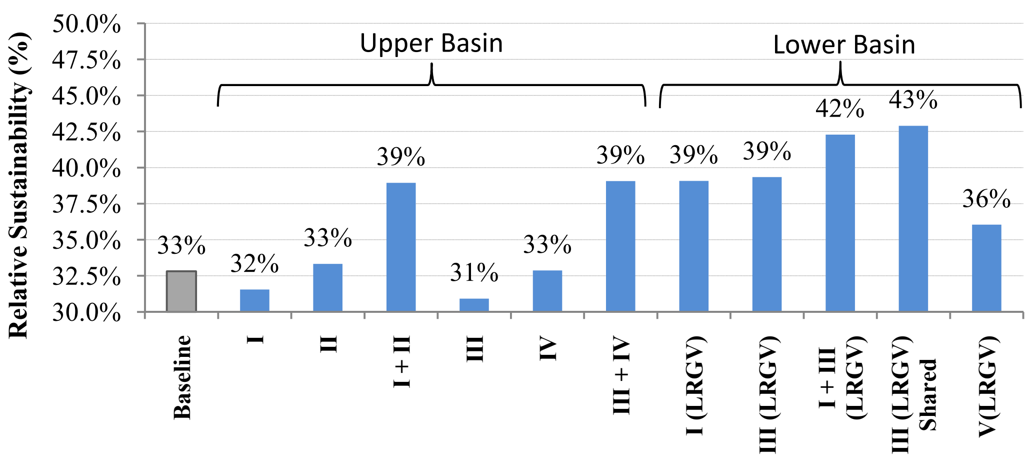


Figure 7-7: Relative Sustainability for the United States

7.1.3.3 Mexico

Figure 7-8 shows the relative sustainability index for Mexico water users' group. For upper basin scenarios, three scenarios provide benefits: (1) the PADUA program coupled with groundwater banking in DR-005 Delicias (I+II) because it improves the water management of DR-005; (2) improvements in the infrastructure due to Minute 309 because it improves the treaty obligations and (3) Minute 309 with the delivery of the savings in an environmental pattern (III+IV) because it improves the treaty obligations and the environmental requirements. For lower basin scenarios, the scenarios related with improvement of infrastructure of DR-025 Bajo Rio Bravo (III(LRGV), I+III(LRGV) and III(LRGV)Shared) provide the most benefits for Mexico's water users. The reduction in the water demand of DR-025 improves the water management of this water users' group. Notice that the reduction in the water demands for the U.S. also provides benefits for Mexico.

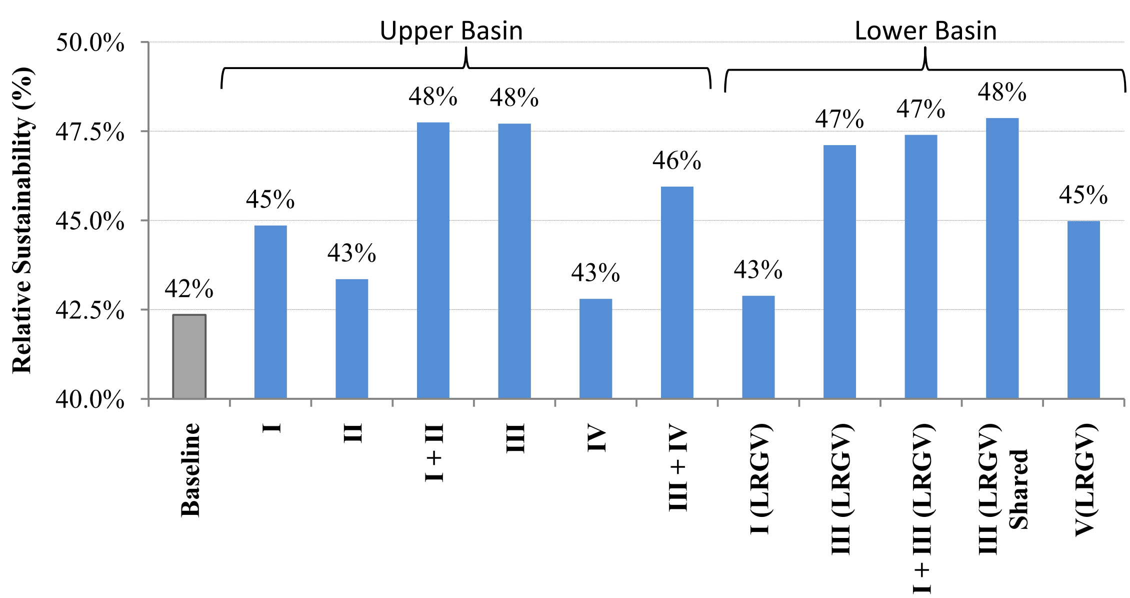


Figure 7-8: Relative Sustainability for Mexico

7.1.3.4 Environment

Figure 7-9 shows the relative sustainability results for environmental requirements group in the Conchos sub-basin. Only results for upper basin scenarios are presented because results for the lower basin do not change with respect of the *Baseline* scenario. Two scenarios provide most benefits: (1) delivering environmental flows to the system (IV); and (2) Minute 309 with the delivery of the savings in an environmental pattern (III+IV). On the contrary, the rest of the scenarios aggravate the environmental conditions. Two scenarios negatively affect the most the environment: (1) the PADUA program coupled with groundwater banking in DR-005 Delicias (I+II) because it reduces the variability in the hydrographs required for the environment; and (2) Minute 309 because it simply delivers the water savings in an arbitrary pattern (December and January). These results show that redistributing the delivery of the savings of Minute 309 in an environmental pattern can improve the environmental conditions at the Rio Conchos sub-basin.

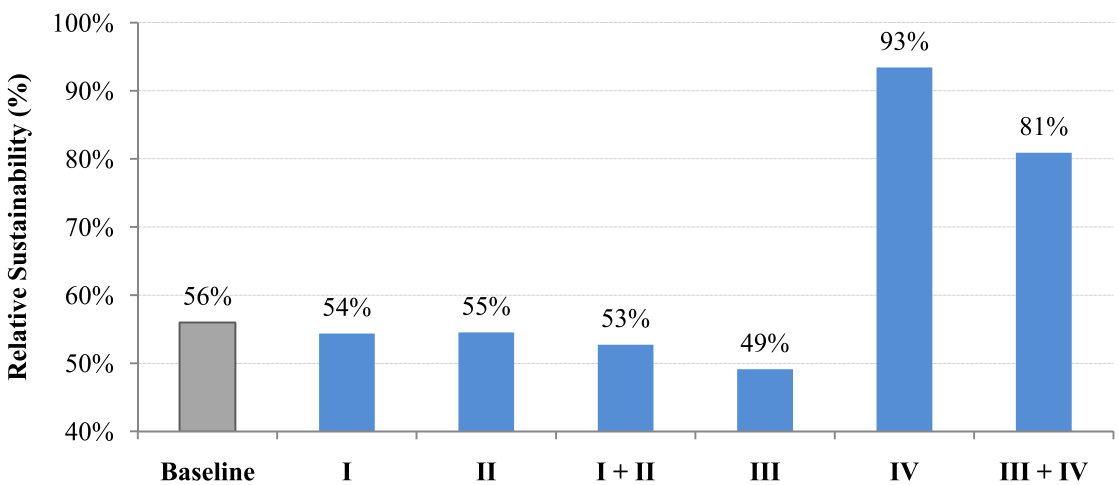


Figure 7-9: Relative Sustainability for Environmental requirements group in the Rio Conchos sub-basin

7.1.4 Summary of Results

For the upper basin, two scenarios have been identified to provide benefits for most of the water system:

- Scenario I + II - Buyback of water rights through the PADUA program coupled with groundwater banking in DR-005 Delicias. This scenario provides the most benefits for DR-005 Delicias in the upper basin
- Scenario III + IV - Improvement in infrastructure due to Minute 309 with the delivery of the savings in an environmental pattern. This scenario provided a good balance of benefits for the environment and treaty obligations.

This policy combination is intended to improve the water management of DR-005 Delicias, the treaty obligations and the environment, which so far has been neglected in the whole basin. The aim is to counteract the negative effects on the environment of scenario I+II with scenario III+IV which improves the environment and the treaty obligations.

For the lower basin, all the scenarios provided benefits to the system; however, two scenarios provide more benefits to the system:

- Scenario III (LRGV) Shared – Improvement in the infrastructure of DR-025 Bajo Rio Bravo and sharing of the water savings with Water Master Section 8-13. This scenario improves the water management for both water users and the treaty obligations.
- Scenario I + III (LRGV) – Buyback of water right and improvement in the infrastructure of DR-025 Bajo Rio Bravo. This scenario improves the water management. This scenario also improves the water management for WMS 8-13 and the treaty obligations.

These lower basin scenarios promote benefits for water users in both countries and the treaty obligations.

Chapter 8 Meta-scenarios Results

This chapter presents the results of *Meta-scenarios* integrated of policies that improve the water management in the system identified in Chapter 7. Meta-scenarios are combination of basic policies that provide benefits to water users, treaty obligations and environmental requirements. First, two meta-scenarios are defined and described. Second, results are shown for individual and groups of water users. These results are compared with the *Baseline* and *Current* scenarios. Third, results from the *Current, Baseline* and the meta-scenarios are displayed geographically in order to identify regions at risk and regions that are benefited from the policies proposed. Forth, conclusions are derived from the results, which include policies to be applied immediately and in the short term to improve the water management in the Rio Grande/Rio Bravo basin.

8.1 DEFINITION

Meta-scenarios are scenarios integrated of policies that provide benefits to the system. The *Baseline* scenario was used, as a point of comparison, to identify policies (or combination of policies) that improves the water management of the system. The *Baseline* scenario represents the system before any policy was implemented (<2004) and it helps quantifying the benefits and worsening due to any water management policies (implemented or proposed).

Since certain policies have been implemented in the basin and cannot be ignored, it is necessary to define a scenario that considers the systems as it is actually working. For this purpose, the *Current* scenario is introduced to represent the actual water management in the Rio Grande/Rio Bravo basin, after 2004. This scenario considers: (a) the buyback of water rights due to the PADUA program [investment of $29.5 million];

(b) the improvement in the infrastructure due to Minute 309 [investment of $189 million] (delivering the water savings each December and January) and (c) the reduction in the water allocation for Water Master Section users in the U.S., no investment considered. The total investment estimated for the current scenario is $218.5 million [$2,753 million pesos, monetary exchange 12.6 pesos per dollar].

Based on chapter seven results (*Baseline* Vs Basic Scenarios) and including the policies already implemented in the actual water management of the basin (*Current* scenario), two meta-scenarios are proposed:

- *Meta-scenario A* – This meta-scenario considers <u>immediate actions</u> to improve the water management in the basin. It must be considered as policies that will provide immediate benefits for the Rio Grande/Rio Bravo basin. In the upper basin, Meta-scenario A considers the combination of the PADUA program (a policy already implemented) coupled with the groundwater banking (I + II) [no investment defined]. In addition, it considers the delivery of the water savings due to Minute 309 (a policy already implemented) in an environmental pattern (III + IV) [no investment considered because the water saved in Minute 309 is delivered in an environmental pattern]. For the lower basin, it considers the reduction in the water demand of Water Master Sections (V(LRGV), a policy already implemented) plus buyback of water rights in DR-025 Bajo Rio Bravo (I(LRGV) [investment: $21.7 million]. The estimated cost for Meta-scenario A is $21.7 million [$273 million pesos, monetary exchange 12.6 pesos per dollar].

- ❖ Meta-Scenario B – This meta-scenario consider short term actions to improve the water management in the basin. It must be seen as a set of additional policies of Meta-Scenario A that will extend benefits for water users, treaty obligations and the environment. This meta-scenario is identical to Meta-Scenario A plus the addition in the upper basin of the buyback of water rights until it reduces the agriculture area of DR-005 Delicias to 50,000 ha [investment: $89 million]. For the lower basin, this meta-scenario considers the improvement in infrastructure of DR-025 Bajo Rio Bravo sharing the water savings with WMS 8-13 [investment: $209 million]. The estimated additional cost of Meta-scenario B is $298 million [$3,755 million pesos, monetary exchange 12.6 pesos per dollar].

Table 8-1 describes *Baseline* scenario and the policies considered for *Current* scenario, *Meta-scenario A* and *Meta-scenario B*.

Table 8-1: Meta-scenarios for the Rio Grande/Rio Bravo Basin

Meta-Scenario	Upper Basin	Lower Basin (LRGV)
Baseline	Water management *before* any policy was implemented (<2004). For the U.S. water rights are 70% of the full allocation demand and for Mexico is the demand in 2004.	
Current	Water management *after* three policies were implemented in the basin: Buyback of water rights due to the PADUA program, improvement in infrastructure due to Minute 309 and the reduction in the WMS demand from 70% to 62%. This policy can be seen as the *current conditions* of the basin. This scenario considers: I – Buyback of water rights (PADUA). III - Improvement in infrastructure due to Minute 309. The water savings are conveyed to the Rio Grande *each December and January.*	V(LRGV)- Reduction of WMS 8-13 demand from 70% to 62%.
A	Proposed water management considering *immediate actions* to improve the water management in the basin, including the environment as a user into the basin. This Meta-scenario considers: I + II - Buy Back of water rights (*PADUA*) plus groundwater banking in DR-005 Delicias. III+IV - Improvement in infrastructure (Minute 309) in DR-005 plus savings delivery in an *environmental pattern.*	I(LRGV) - Buy Back of water rights in DR-025. V(LRGV)- Reduction of WMS 8-13 demand from 70% to 62%.
B	Proposed water management considering *short term actions* to mitigate the worsening from the *Current* scenario and to include the environment as a user into the basin. This Meta-scenario considers: I + II - Buy Back of water rights (*Reduction of DR-005 to 50,000 ha*) plus groundwater banking in DR-005 Delicias. III+IV - Improvement in infrastructure (Minute 309) in DR-005 plus savings delivery in an *environmental pattern.*	I(LRGV) - Buy Back of water rights in DR-025. III (LRGV) Shared - Improvement in the infrastructure of DR-025 and sharing of the savings with WMS 8-13. V(LRGV)- Reduction of WMS 8-13 demand from 70% to 62%.

Meta-Scenario A is integrated with policies that can be implemented immediately, with a low initial cost. In the upper basin, Meta-scenario A includes the PADUA program (a policy already implemented) coupled with the groundwater banking, a proposed policy that can be implemented immediately by organizing surface and groundwater users. The infrastructure of irrigation district DR-005 Delicias is ready, in most of the modules, to supply surface and groundwater user with water from the reservoirs (Caballero 2005). For this policy is strongly recommended to determine the hydraulic characteristics of the Meoqui aquifer (storage capacity, hydraulic conductivity, recharge, surface-groundwater interaction, maximum recovery), and then, estimate the expansion of the groundwater pumping and its cost. In addition, it considers the delivery of the water savings due to Minute 309 (a policy already implemented) in an environmental pattern. In this case, it is necessary that authorities agree to change the delivery pattern from an arbitrary December-January schedule to an environmental pattern delivery. For the lower basin it considers the reduction in the water demand of Water Master Sections (WMS) (a policy already implemented) plus buyback of water rights in DR-025 Bajo Rio Bravo. For DR-025 Bajo Rio Bravo, the water rights bought back should come from irrigated areas with salinity problems that have a low or none production (Zatarain et al. 2005), this policy may take two to three years for its completion, based on DR-005 PADUA's program.

Meta-Scenario B is integrated with policies that can be implemented in the short term with a higher initial investment. In the upper basin, Meta-scenario B considers the reduction in the agriculture area of DR-005 Delicias to 50,000 hectare. Data from CONAGUA (2003 and 2009) show this reduction is reasonable: 1) the average irrigated area is estimated of 49,574 ha. (CONAGUA 2003), and 2) the irrigated area in 2008, an average year, was 52,323 hectare (CONAGUA 2009). The objective of this policy is to retire from the system "paper water rights" that are not frequently supplied, only during wet years; and also to compensate farmers that have this "paper water rights" and who usually do not receive this water. This policy is recommended to be implemented after the buyback of water rights in DR-025 for the following reasons: a) economic reasons, it would be very difficult for the Mexican federal government to invest money to buy back water rights from DR-025 Bajo Rio Bravo and DR-005 Delicias at the same time, and b) political reasons, DR-005 has already been benefited with a buyback program (PADUA), it would be politically correct to benefit other irrigation districts, such as DR-025 Bajo Rio Bravo, before buying back water rights in DR-005 Delicias once again. For the lower basin, Meta-scenario B considers the improvement in infrastructure of DR-025 Bajo Rio Bravo sharing the water savings with WMS 8-13 (WMS 8-13). Considering the significant amount of investment necessary to improve the infrastructure, \$209 million, this policy proposes sharing the cost and benefits between both irrigation districts, DR-025 Bajo Rio Bravo and WMS 8-13.

8.2 Results by User

Similarly to the previous section, results for selected water users are presented to evaluate and verify that the policies proposed in the meta-scenarios improve the water management for each water user.

8.2.1 DR-005 Delicias, DR-025 Bajo Rio Bravo and WMS 8-13

Table 8-2 and Figure 8-1 show the results for the *Baseline, Current* and *Meta-scenario A* and *B* for irrigations districts: DR-005 Delicias, DR-025 Bajo Rio Bravo and Water Master Section 8-13 (WMS 8-13).

For DR-005 Delicias, results show the water management got worse from the *Baseline* to the *Current* scenario, which means that the policies already implemented negatively affected the water supply for this user. The water supply in Meta-scenario A improves with respect to the *Current* scenario even though both scenarios have the same water demand. Two policies make the difference to obtain these results: the groundwater banking policy in the Meoqui aquifer and the delivery of the water savings of Minute 309 in an environmental pattern. Furthermore, reducing the agriculture area of DR-005 Delicias from 90,000 to 50,000 hectare increases the water sustainability for this user in Meta-scenario B.

For DR-025 Bajo Rio Bravo, the water management slightly improves from the *Baseline* to the *Current* scenario, from 48% to 50%. In Meta-scenario A, where its water demand is reduced, the water supply improves from 50% to 56%, with respect to the Current scenario. Even though the water savings due to the improvement of infrastructure promoted in Meta-scenario B are shared with WMS 8-13, its water supply improves significantly from 50% in the *Current* scenario to 62% in Meta-scenario B.

Table 8-2: Sustainability Index for DR-005, DR-025 and WMS 8-13; Baseline, Current and Meta-scenarios

Water User	Scenario	Demand ($1X10^6$ m^3/year)	Sustainability (%)
DR-005	Baseline	1131	21%
	Current	681	10%
	MS-A	681	24%
	MS-B	419	57%
DR-025	Baseline	861	48%
	Current	861	50%
	MS-A	761	56%
	MS-B	514	62%
WMS 8-13	Baseline	1261	32%
	Current	1117	43%
	MS-A	1117	43%
	MS-B	1117	49%

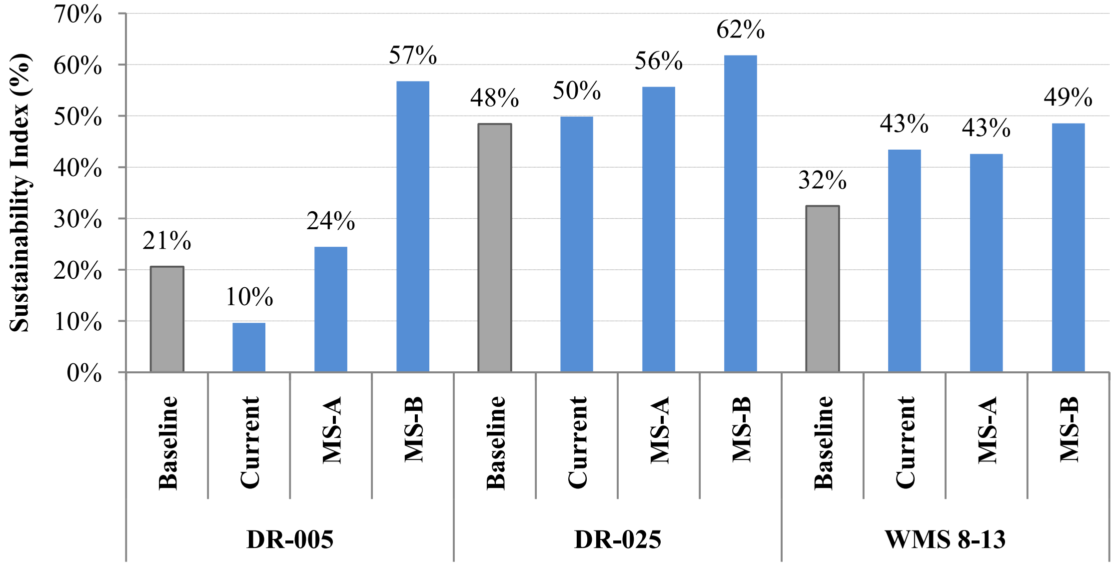


Figure 8-1: Sustainability Index for DR-005, DR-025 and WMS 8-13; Baseline, Current and Meta-scenarios

For WMS 8-13, water management improves from 32% in the *Baseline* to 43% in the *Current* scenario. Meta-scenario A does not provide any benefits for this water user, conserving the sustainability index at 43%, with respect to the *Current* scenario. The sharing of the water savings, due to the improvement of infrastructure promoted in Meta-scenario B, improves the water sustainability for this user from 43% in the *Current* scenario to 49% in Meta-scenario B.

In summary, for the *Current* scenario, mixing results are obtained. Meanwhile, this scenario improves the water management for DR-025, it does not make any change for WMS 8-13 and it negatively affect DR-005. On the contrary, results from Meta-scenarios A and B improves the water management for any of these water users.

8.2.2 Treaty Obligations

For the treaty obligations, water management improves from 51% in the *Baseline* to 68% in the *Current* scenario (Table 8-3 and Figure 8-2). Meta-scenario A slightly reduces the water management for this international obligation, from 68% in the *Current* scenario to 64% in Meta-scenario A. Performance criteria results of the treaty obligations show that the vulnerability and standard deviation decreases, which is a good sign, and also the reliability does not decrease, another good sign, but the resilience decrease and as a consequence, the sustainability slightly decrease. Similarly, Meta-scenario B slightly reduces the treaty obligations, from 68% in the *Current* scenario to 66% in Meta-scenario B. In this case reliability increases and resilience does not decrease, but the vulnerability and standard deviation increase and thus the sustainability index slightly decrease.

Table 8-3: Sustainability Index for Treaty Obligations; Baseline, Current and Meta-scenarios

Water User	Scenario	Demand ($1X10^6$ m^3/Cycle)	Sustainability (%)
Treaty Obligations	Baseline	2159	51%
	Current	2159	68%
	MS-A	2159	64%
	MS-B	2159	66%

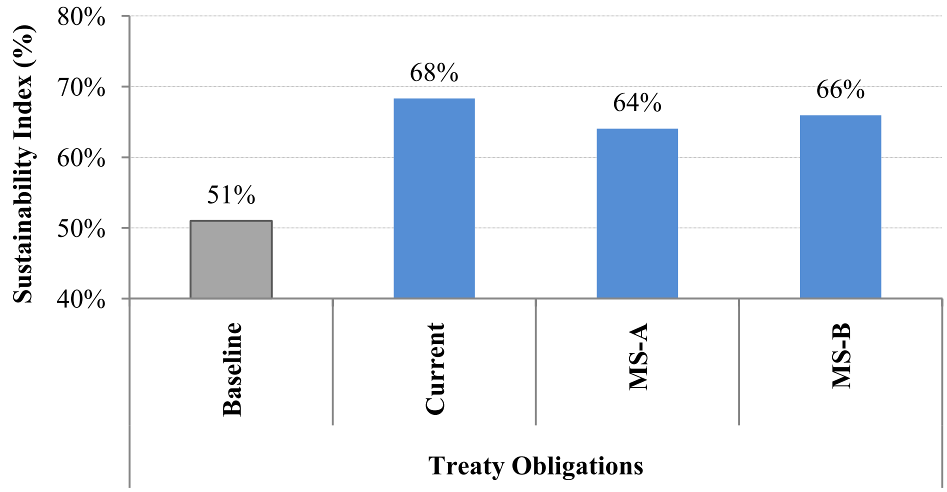


Figure 8-2: Sustainability Index for Treaty Obligations; Baseline, Current and Meta-scenarios

8.2.3 Environment

Table 8-4 and Figure 8-3 show the results for all the environmental control points evaluated in the Environmental flow policy: VM1 Cuchillo Parado, VM2 Potrero, VM3 Estación Conchos, VMc Camargo, and VMd C. Ortiz. For environmental control points VM1, VM2, VM3 and VMd, their water supply get worse in the *Current* conditions with respect to the *Baseline* scenario. For VMc, the environmental water supply improves from the *Baseline* to the *Current* scenario. For Meta-scenario A, the water supply improves in all the environmental control points, with respect to the *Current* scenario. Moreover, in Meta-scenario B the water sustainability improves more, with respect of Current and Meta-scenario A.

Table 8-4: Sustainability Index for Environmental Control points; Baseline, Current and Meta-scenarios

Control Point	Scenario	Demand ($1X10^6$ m^3/year)	Sustainability (%)
VM 1	Baseline	208	61%
	Current	319	41%
	MS-A	292	100%
	MS-B	353	100%
VM 2	Baseline	174	81%
	Current	270	61%
	MS-A	246	100%
	MS-B	299	100%
VM 3	Baseline	20	81%
	Current	24	79%
	MS-A	23	100%
	MS-B	26	100%
VMc	Baseline	23	25%
	Current	23	44%
	MS-A	23	75%
	MS-B	23	75%
VM d	Baseline	52	31%
	Current	57	30%
	MS-A	56	59%
	MS-B	59	76%

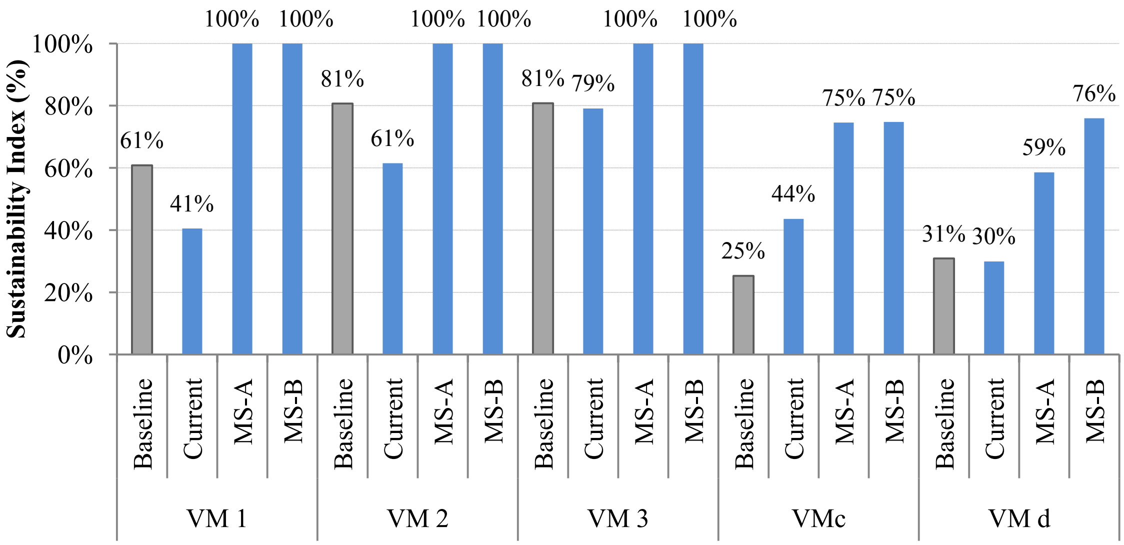


Figure 8-3: Sustainability Index for all environmental control points in the Conchos basin; Baseline, Current and Meta-scenarios

8.3 Results by Group

The relative sustainability results of the four water user's groups are presented:

1. *Rio Grande/Rio Bravo,*
2. *United States,*
3. *Mexico,* and
4. *Environment*

8.3.1 Rio Grande/Rio Bravo

The relative sustainability index of the Rio Grande/Rio Bravo for the *Baseline*, *Current* and Meta-scenario A and B is shown in Figure 8-4. The relative sustainability index of the Rio Grande/Rio Bravo considers all water users for both countries, the treaty obligations of water delivery from Mexico to the U.S., and all the environmental requirements in the Rio Conchos Basin, the water management in the *Current* scenario has improved with respect of the *Baseline* scenario, from 40% to 47% respectively. Meta-scenario A improves the water management from 47% in the Current scenario to 50% in Meta-scenario A. Moreover, the policies promoted in Meta-scenario B improve the water management from 47% in the *Current* scenario to 55% in Meta-scenario B. In summary, the policies implemented in the Current scenario and the policies proposed in Meta-scenario A and B policies improve the water management in the Rio Grande/Rio Bravo basin.

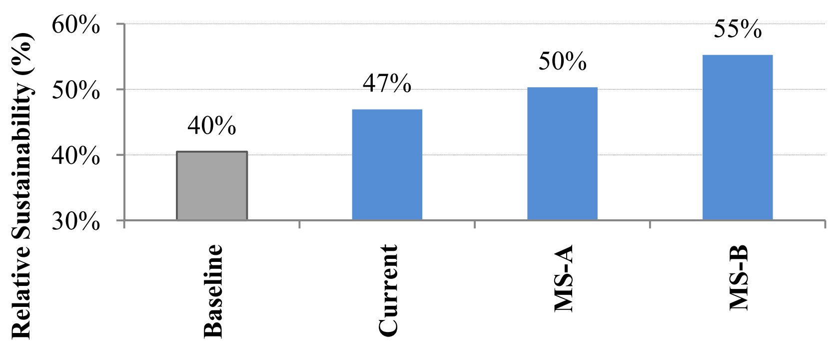


Figure 8-4: Relative Sustainability for the Rio Grande/Rio Bravo group; Baseline, Current and Meta-scenarios

8.3.2 United States and Mexico

The relative sustainability index of the United States and Mexico's group for the *Baseline*, *Current* and Meta-scenario A and B is shown in Figure 8-5. For both groups the *Current* scenario improves the water management with respect of the *Baseline* scenario from 33% to 42% for the U.S and from 42% to 49% for Mexico. Even though in Meta-scenario A is considered the delivery of water for environmental purposes, the water management in both countries is not affected because the relative sustainability is the same for *Current* and Meta-scenario A. This means that the environment can be included into the water management without worsening the actual water supply for both countries. Meta-scenario B further improves the water management for both countries.

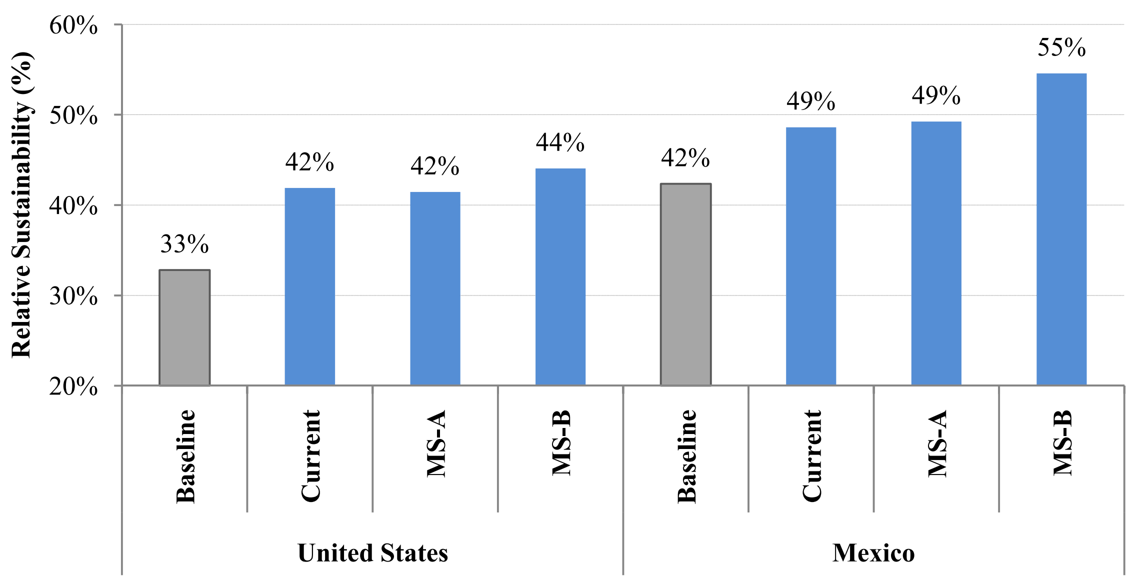


Figure 8-5: Relative Sustainability for the United States and Mexico water users' group; Baseline, Current and Meta-scenarios

8.3.3 Environment

The relative sustainability index of the Environmental requirements group for the *Baseline*, *Current* and Meta-scenario A and B is shown in Figure 8-6. Results show that the current policy is worsening the water supply for the environment, from 56% in the *Baseline* to 49% in the *Current* scenario. The delivery of the water savings due to Minute 309 in an environmental pattern considered in Meta-scenario A significantly improve the environmental flows in the Rio Conchos basin, from 49% in the *Current* scenario to 95% in Meta-scenario A. Similarly, Meta-scenario B provides more benefits for the environment than the *Current* conditions.

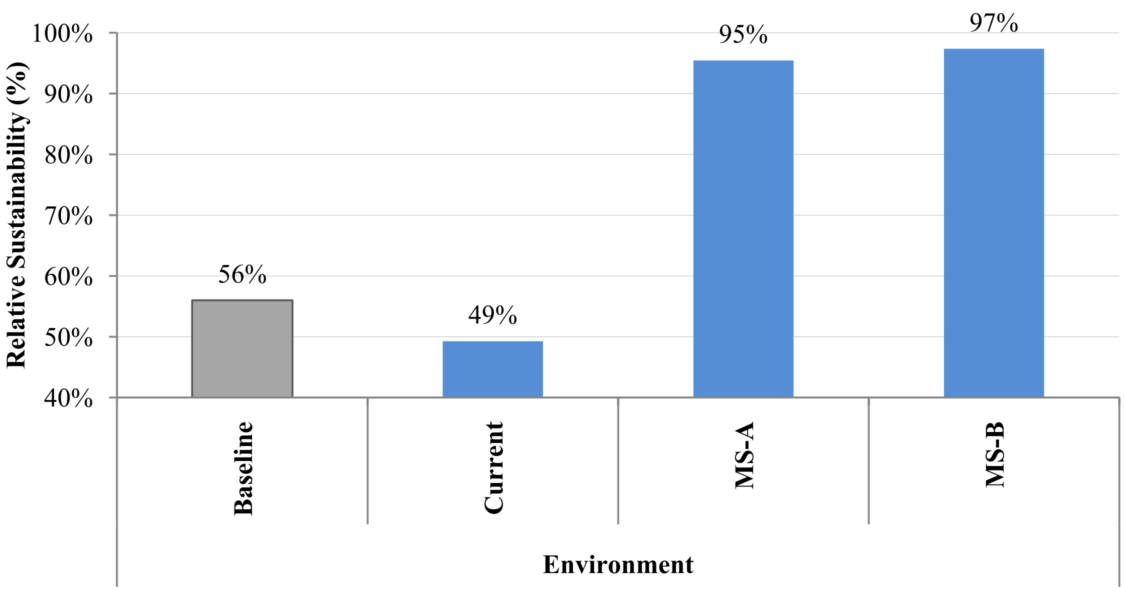


Figure 8-6: Relative Sustainability for Environmental requirements group; Baseline, Current and Meta-scenarios

8.4 RESULTS BY REGION

In order to identify stressed water resources areas, water users have been grouped according to their location in the basin. The relative sustainability for 13 regions (6 in the U.S and 7 in Mexico) has been calculated using equations 3-15 and 3-16. Results of each scenario are compared in order to identify regions where the water management improved or got worse. This comparison is quantified by calculating the differences in the relative sustainability (Δ Rel. Sust.); positive numbers represent an improvement in the water management; on the contrary, negative numbers represent draw backs in the water management.

8.4.1 Baseline and Current Scenarios

Table 8-5 shows the relative sustainability and its change of the 13 regions for *Baseline* and *Current* scenarios. Table 8-6 summarizes the relative sustainability by group for *Baseline* and *Current* scenarios. Figure 8-7 shows the relative sustainability by region for the *Baseline* scenario.

Table 8-5: Relative Sustainability per region; Baseline and Current scenarios

Region	Name	Rel. Sust. (%) Baseline	Rel. Sust. (%) Current	Δ Rel. Sust. (%)
US - 1	Forgotten River	8	8	0
US - 2	Big Bend reach	100	100	0
US - 3	Pecos river	29	29	0
US - 4	Devils River	100	100	0
US - 5	Amistad - Falcon	46	58	**+ 12**
US - 6	Lower Rio Grande Valley	38	52	**+ 14**
MX - 1	Cd. Juarez - Ojinaga	38	38	0
MX - 2	Rio Conchos	27	23	**- 4**
MX - 3	Ojinaga - Amistad	100	100	0
MX - 4	Rio Salado	26	26	0
MX - 5	Amistad - Falcon	71	72	**+ 1**
MX - 6	Rio San Juan and Alamos	33	33	0
MX - 7	Bajo Rio Bravo	55	56	**+ 1**

Table 8-6: Change in the Sustainability per group; Baseline and Current scenarios

Group	Rel. Sust. (%) Baseline	Rel. Sust. (%) Current	Δ Rel. Sust. (%)
Rio Grande/Rio Bravo	40	47	**+ 7**
United States	33	42	**+ 9**
Mexico	42	49	**+ 7**
Treaty Obligations	51	68	**+ 17**
Environment	56	49	**- 7**

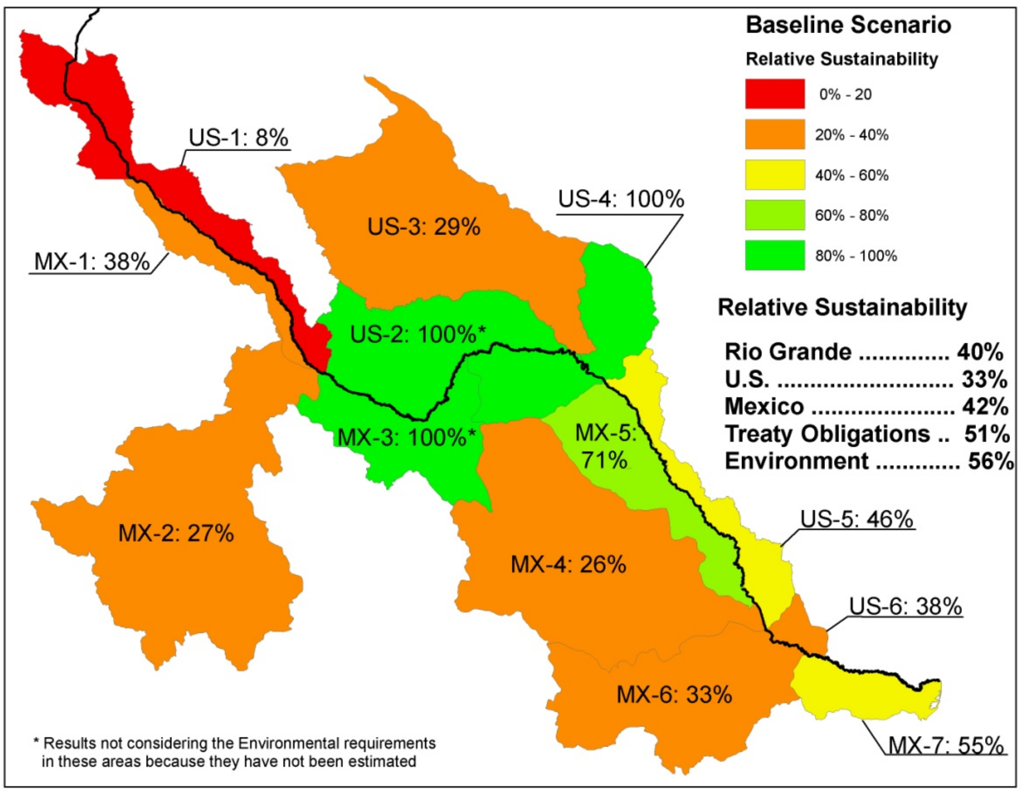


Figure 8-7: Relative Sustainability for regions; Baseline scenario

Figure 8-7 shows the relative sustainability for the *Baseline* scenario, which represents the water management before any policy was implemented in the basin (<2004). With this display of results is possible to identify regions at risk where water management must be improved. For the U.S., the Forgotten River (US-1), Pecos (US-3), Lower Rio Grande Valley (US-6) and Amistad-Falcon (US-5) are the areas with the lowest relative sustainability indices. For Mexico, the Rio Salado (MX-4), Rio Conchos (MX-2), Rio San Juan (MX-6) and Cd. Juarez-Ojinaga (MX-1) are the areas with the lowest relative sustainability indices.

Figure 8-8 shows the change in the relative sustainability (Δ Rel. Sust.) of the *Current* scenario, compared to the Baseline scenario. This figure shows the regions where the water management have been improved, remaining the same or worsen, due to the policies implemented in the *Current* scenario.

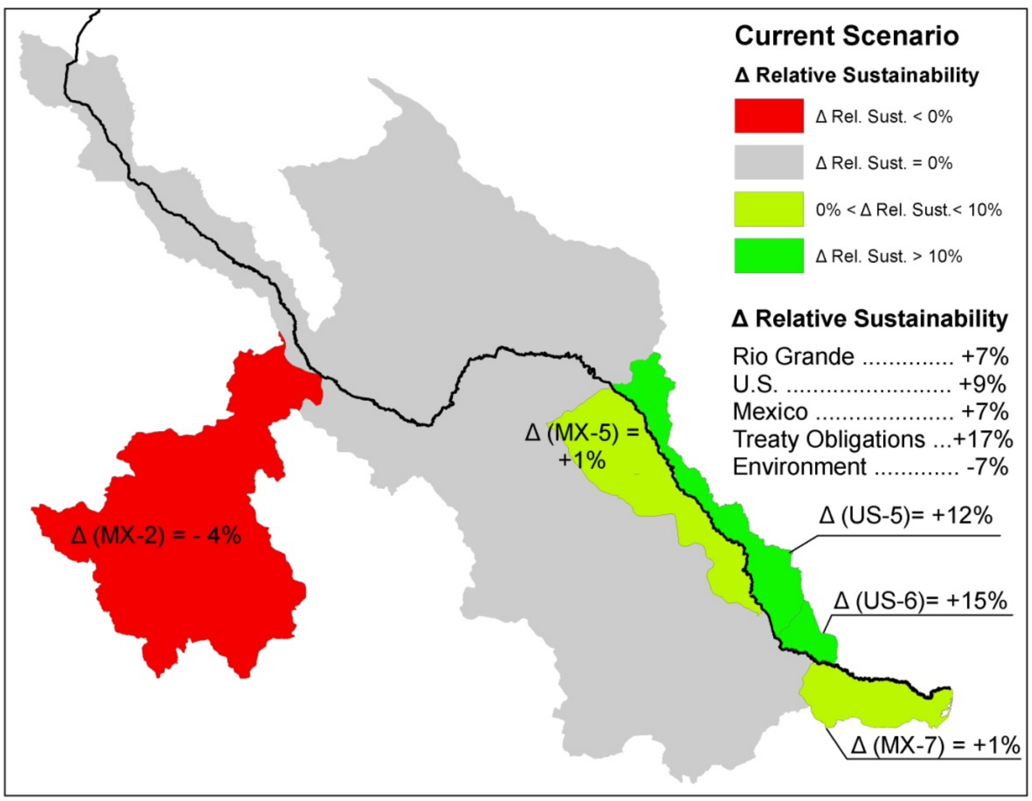


Figure 8-8: Change in the Relative Sustainability, Current Vs. Baseline scenario

For the U.S., the water management policies implemented in the Current scenario improved the water management for U.S. water users by 9% (from 33% to 42%), with regional benefits in Amistad-Falcon (US-5) region by 12% and the Lower Rio Grande Valley (US-6) by 14%. The reduction in the water allocation from 70% to 62% for water users other than domestic, municipal or industrial, improved the water management of the basin. In addition the improvement in the delivery of Treaty Obligations by 17% also benefited the water management for these areas. More water was available and the water demand was lower than in the baseline scenario.

For Mexico, the water management improved by 7% (from 42% to 49%), with mixing results. Meanwhile the treaty obligations improved by 17% (from 51% to 68%) and water management in regions Amistad-Falcon (MX-5) and Bajo Rio Bravo (MX-7) slightly improved by 1%in each region; the water management in the Rio Conchos sub-basin (MX-2) got worse by 4%. The policies already implemented in Rio Conchos sub-basin have improved water users downstream this basin and the treaty obligations but it has worsen the water supply in this sub-basin.

For the environment, the conditions got worse than the *Baseline* scenario, with a reduction in the relative sustainability of 7% (from 56% to 49%) in this water group. The policies implemented in the Rio Conchos aggravate the already threatened environmental conditions in this sub-basin.

In general, considering water users of both countries, international obligations and the environment, the Current scenario improves the water management by 7% (from 40% to 47%), compared with the Baseline scenarios.

8.4.2 Meta-Scenarios

Table 8-7 shows the relative sustainability and its change (Δ Rel. Sust.) of the 13 regions for Current, Meta-scenarios A and B. Table 8-8 summarizes the relative sustainability by group for *Current*, Meta-scenarios A and B. Figure 8-9 shows the relative sustainability by region for the *Current* scenario.

Table 8-7: Relative Sustainability per region; Current and Meta-scenarios

		Relative Sust. (%)			Δ Rel. Sust.	
Region	Name	Current	MS - A	MS - B	MS - A	MS - B
US - 1	Forgotten River	8	8	8	0	0
US - 2	Big Bend reach	100	100	100	0	0
US - 3	Pecos river	29	29	29	0	0
US - 4	Devils River	100	100	100	0	0
US - 5	Amistad - Falcon	58	58	61	0	**+ 3**
US - 6	Lower Rio Grande Valley	52	52	56	0	**+ 4**
MX - 1	Cd. Juarez - Ojinaga	38	38	38	0	0
MX - 2	Rio Conchos	23	30	49	**+ 7**	**+ 26**
MX - 3	Ojinaga - Amistad	100	100	100	0	0
MX - 4	Rio Salado	26	26	26	0	0
MX - 5	Amistad - Falcon	72	72	77	0	**+ 5**
MX - 6	Rio San Juan and Alamo	33	33	33	0	0
MX - 7	Bajo Rio Bravo	56	61	69	**+ 5**	**+ 13**

Table 8-8: Change in the Sustainability per group; Current and Meta-scenarios

		Rel. Sust. (%)		Δ Rel. Sust. (%)	
Group	Current	MS - A	MS - B	MS - A	MS - B
Rio Grande/Rio Bravo	47	50	55	**+ 3**	**+ 8**
United States	42	42	44	0	**+ 2**
Mexico	49	49	55	0	**+ 6**
Treaty Obligations	68	64	66	**- 4**	**- 2**
Environment	**49**	**95**	**97**	**+ 46**	**+ 48**

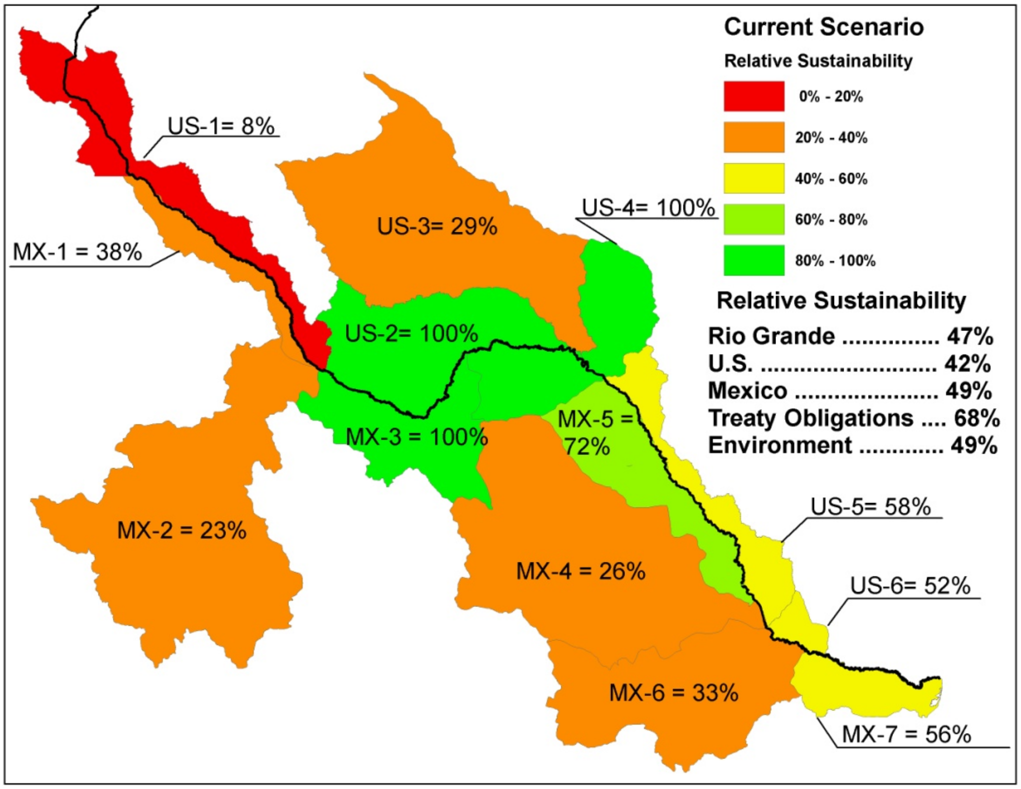


Figure 8-9: Relative Sustainability for regions; Current Scenario

Figure 8-9 shows the relative sustainability for the *Current* scenario, which represents the systems in its actual conditions with the current water management (>2004). Results from the *Current* scenario are used as a point of comparison for Meta-scenarios A and B. Notice that in both of the countries, the same regions are at risk in the *Current* scenario with respect to the *Baseline* scenario.

Along the border, three areas are of particular interest because of their complex water management: the Forgotten River (US-1/MX-1), the Big Bend area (US-2/MX-3), and the Lower Rio Grande Valley (US-6/MX-7). The forgotten river sub-basin (US-1/MX-1) is the most stressed area in the basin, the growing water demand for municipal and industrial use in El Paso-Cd. Juarez plus the agriculture use of El Paso Water

Irrigation District #1 (EPWID #1) in Texas and DR-009 Valle de Juarez in Mexico have exhausted the water resources in the area; the water demands are larger than the natural availability of water. In the U.S., the system is so stressed that water planning includes: conjunctive use of surface-groundwater, harvesting of rainwater, recharge of groundwater with treated surface water, treatment and re-use of agricultural drain water, leasing of water permits, water desalination systems, among other policies (TWDB 2010.a, b and c.). In Mexico, the system is so tight, that agriculture water rights have been transferred to the municipality of Ciudad Juarez and the wastewater treated from this city is now used for agriculture purposes (CONAGUA 2004). These conditions are captured in the results with a sustainability index of 8% for the US-1 and 38% for MX-1.

After the forgotten river, the Lower Rio Grande Valley (US-6/MX-7) is the most stressed area along the border; water supply in this region depends on the water use in the whole basin. Water management in the tributaries consumes the water that is produced before it reaches the Rio Grande/Rio Bravo main stream. The water supply of the Lower Rio Grande Valley depends on the storage of the international reservoirs, which depend on the water from the tributaries. During drought periods, almost no water flows to the Rio Grande/Rio Bravo from the tributaries, storage in both international reservoirs is greatly decreased and the water supply for this area is threatened. For the *Current* scenario, the sustainability index for MX-7 and US-6 are 56% and 52%, respectively.

The Big Bend region (US-2/MX-3) is an environmental stressed area. Even thought the relative sustainability is 100%, this calculation does not consider the environmental needs for this region; the environmental flows for the Big Bend reach have not been defined yet. In addition, most of the water in the Big Bend area comes from the Rio Conchos (75% on average) and is managed by CONAGUA, who do not have a defined policy to deliver water from the Rio Conchos to the Rio Grande/Rio Bravo; the water management in this area is uncertain. An international team has been working to define the environmental flows along this reach (WWF 2006; Sandoval-Solis and McKinney 2009); as well as a policy to provide environmental flows to the Big Bend reach. There is evidence that environmental degradation has happened (Dean and Schmidt 2011), and it is highly possible that this degradation will continue in the future if no action is taken; thus, the environment conditions in this area are highly threatened.

In addition Figure 8-9 shows four sub-basins with a stressed water management: Pecos (US-3), Rio Salado (MX-4), Rio Conchos (MX-2) and Rio San Juan (MX-6). In these four sub-basins, the water demand is larger than the natural availability of water (CONAGUA 2008.b), the water resources are over-allocated. This problematic is aggravated with the high variability of water resources.

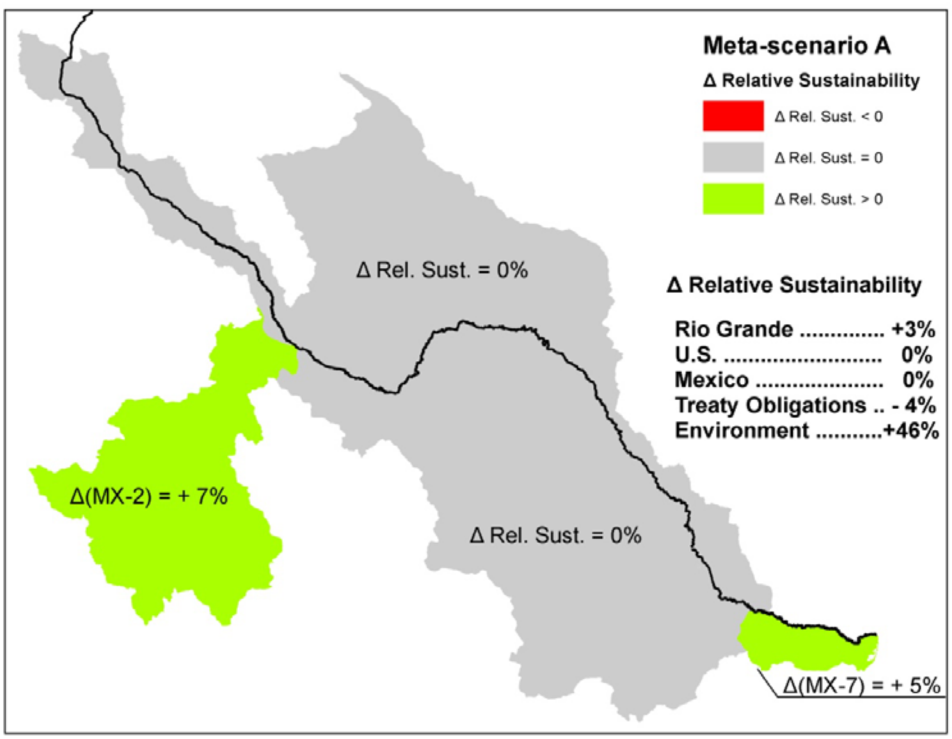


Figure 8-10: Change in the Relative Sustainability, Meta-scenario A Vs. Current Scenario

Figure 8-10 shows the change in the relative sustainability of the Meta-scenario A, compared to the *Current* scenario. This figure shows the regions where the water management have been improved, remaining the same or worsen, due to the policies implemented in the Meta-scenario A.

For the U.S. and Mexico, the water management policies implemented in Meta-scenario A do not affect their water management even though policies are implemented to deliver water to the environment. This is an important result since environmental requirements have always been neglected or not considered because they are thought to harm anthropogenic water users. These results prove the opposite, at least for the environmental requirement in the Rio Conchos sub-basin. The delivery of the water savings due to Minute 309 in an environmental patter improves the environment by 46% with respect to the *Current* scenario. This is a significant improvement from a relative sustainability of 49% in the *Current* scenario to 95% in Meta-scenario A. In the U.S., no region is harmed with the policies implemented in Meta-scenario A. For Mexico, in the upper basin, the groundwater banking policy coupled with the buyback of water rights improved the water management in the Rio Conchos sub-basin (MX-2) by 7%. In the lower basin, the buyback of water rights in DR-025 improved the water management of the Bajo Rio Bravo region (MX-7) by 5%. For the treaty obligations, its sustainability index slightly decreases by 4%. In Meta-scenario A the reliability increased and the Vulnerability and the Standard Deviation decreased with respect to the *Current* scenario; however, the resilience slightly decreased and this is the reason why the sustainability index slightly decreases by 4%. In summary, considering water users of both countries, international obligations and the environment, Meta-scenario A improves the water management by 3% (from 47% to 50%).

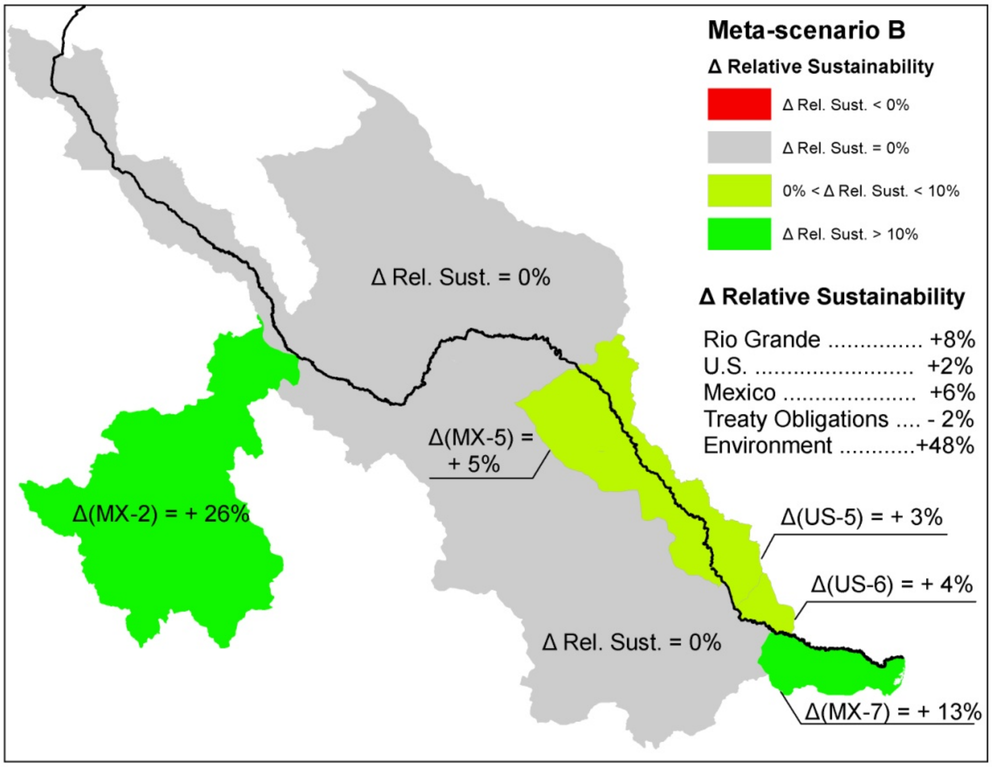


Figure 8-11: Change in the Relative Sustainability, Meta-scenario B Vs. Current Scenario

Figure 8-11 shows the change in the relative sustainability of the Meta-scenario B, compared to the *Current* scenario. This figure shows the regions where the water management have been improved, remaining the same or worsen, due to the policies implemented in the Meta-scenario B.

For the U.S., the policies proposed in Meta-scenario B improved the water management 2% (from 42% to 44%) with respect to the *Current* scenario. Sharing the water savings due to the infrastructure improvements in DR-0025 Bajo Rio Bravo with WMS 8-13 improved the water management in Amistad-Falcon region (US-5) by 3% and in the Lower Rio Grande Valley (US-6) by 4%. For Mexico, Meta-scenario B improved the water management by 6% (from 49% to 55%), with respect to the *Current* scenario. The improvement in the infrastructure coupled with the reduction in water rights of DR-

025 Bajo Rio Bravo increased the relative sustainability of the Bajo Rio Bravo region (MX-7) by 13% and the Amistad-Falcon region (MX-5) by 5%. Also, the combination of the groundwater banking policy with the reduction of the agriculture area of DR-005 Delicias from 90,000 ha to 50,000 ha improved the water demand in the Rio Conchos sub-basin (MX-2) by 26%. This results shows how over-allocated are the agriculture water rights in the Rio Conchos sub-basin. Similarly to the previous meta-scenario, results for the environment show an important increase in its relative sustainability of 48% (from 49% to 97%). The delivery of the water savings due to Minute 309 in an environmental pattern significantly improves the environmental conditions in the Rio Conchos sub-basin. For the treaty obligations, the sustainability index slightly decreases by 2%; practically, the sustainability is the same than in the *Current* conditions.

In summary, considering water users of both countries, international obligations and the environment, Meta-scenario B improves the water management of the Rio Grande/Rio Bravo by 8% (from 47% to 55%).

8.5 SUMMARY OF RESULTS

This section evaluates the results of the *Current*, Meta-scenario A and B.

- ❖ *Current scenario* – The comparison of the *Baseline* and *Current* scenario shows mixing results. Meanwhile the *Current* policies have improved the water management for several water users (DR-025, WMS 8-13, Treaty obligations) and regions (US-5, US-6, MX-5 and MX-7), it also has decreased the water supply for important users, such as DR-005 Delicias, and it has worsen the environmental conditions in the Rio Conchos sub-basin. The policies implemented in Minute 309 improves the water management for the treaty obligations, water users in the lower basin (Water Master Sections and DR-025); but paradoxically, this policy worse the water supply for DR-005 Delicias and the environment. These negative effects are stronger than the improvements obtained because of the buy backs of water rights due to the PADUA program. In contrast, the reduction in the full allocation demand for U.S. water users from 70% to 62% significantly improved the water management for the U.S. Even though on the overall *Current* scenario results shows an improvement in the water management of the Rio Grande/Rio Bravo by 6%, compared with the *Baseline* scenario, the policies implemented in this scenario worsen the water management for important users, regions and the environment.

❖ *Meta-scenario A* – The comparison of Meta-scenario A and *Current* scenario shows improvements in the water management. The policies proposed in Meta-scenario A do not affect the water management in the U.S. and Mexico meanwhile it significantly improves the water supply for environmental purposes, by 46%. The policies proposed in Meta-scenario A can be applied immediately to provide benefits to water users, such as the groundwater bank policy for DR-005 Delicias; to the environment, such as the delivery of the water saved in Minute 309 in an environmental pattern, and other policies are meant to obtain benefits given the characteristics of the user, for instance buying back water rights in DR-025 to retire water rights from irrigated areas with salinity problems. The proposed policies coupled with the already implemented improve the water management in the Rio Grande/Rio Bravo basin. Meta-scenario A also shows that an environmental water management policy can be applied without harming human water users. This is an important result since environmental requirements have always been neglected or not considered because they are thought to harm anthropogenic water users. In this scenario water users located in the Rio Conchos sub-basin and the Bajo Rio Bravo region are benefited. The treaty obligations slightly decrease its performance by 4%. The overall improvements estimated for the Rio Grande/Rio Bravo are 3%, with respect to the *Current* scenario.

❖ *Meta-scenario B* – The comparison of Meta-scenario B and *Current* scenario shows significant improvements in the water management. The policies proposed in Meta-scenario B are strategies with higher initial investment that can be applied in the short term. These policies are intended to share benefits and investment, such as the improvement in infrastructure in DR-025 Bajo Rio Bravo and the sharing of the investment and the water saved between DR-025 Bajo Rio Bravo and WMS 8-13; or policies intended to compensate water users by retiring from the system water rights that are not frequently supplied, such as the reduction in the irrigated area of DR-005 Delicias from 90,000 to 50,000 hectare. The policies proposed in Meta-scenario B improve the water management in the U.S. and Mexico by 2% and 6%, respectively. Results show an increment in the environmental relative sustainability of 48%. This scenario significantly improves the water supply for environmental purposes. Again, this policy shows that an environmental water management policy can be applied without harming anthropogenic water users. Water users located in the Rio Conchos (MX-2), Bajo Rio Bravo (MX-7), Amistad Falcon (US-5 and MX-5) and Lower Rio Grande Valley (US-6) regions are benefited in their water supply. Practically the performance of the treaty obligations is the same as in the Current scenario, with a slight decrease of 2%. The overall improvements of Meta-scenario B estimated for the Rio Grande/Rio Bravo are 8%, with respect to the *Current* scenario.

Meta-scenario A and B provide benefits to water users from Mexico, the U.S. and the environment. However, both scenarios slightly decrease the water management of Treaty obligations, from a sustainability index of 68% in the *Current* scenario, to a sustainability index of 64% and 66% in Meta-scenario A and B, respectively. This might be an issue to overcome, considering that authorities from both countries have discussed about improving the delivery of water for treaty obligations because of the water debt in cycles 25 and 26 (1992-2002). Recent research has shown that a risk analysis and drought forecasting can improve the delivery of Treaty obligations (Sandoval-Solis and McKinney 2010). Further research is necessary to define and include a drought forecasting policy for Treaty Obligations.

Chapter 9 Conclusions

9.1 AIM OF THE DISSERTATION

The objectives of this dissertation are:

1. Construct, calibrate and validate a water resources planning model that represents the hydro-physical and regulatory framework of a large-scale transboundary basin.
2. Define a methodology to evaluate and compare different scenarios of water management policies.
3. Utilize the water resources planning model and the methodology defined to evaluate different scenarios for improving water management in the basin.
4. Assess the water planning and management for the transboundary basin.

9.2 DISCUSSION

A hydrologic water planning model for the large scale transboundary Rio Grande/Rio Bravo basin was built using the Water Evaluation and Planning System (WEAP) software. The Rio Grande/Rio Bravo WEAP model represents the water management in the basin; for U.S. water demands it follows the water allocation of the Texas Rio Grande Water Master Program; for Mexican water demands it follows the water allocation according to the Mexican National Water Law and between both countries, it follows the Convention of 1906 and the Treaty of 1944. The model has a total 216 water demands, including surface and groundwater rights, accounting for a total annual demand of 12,679 million m^3. The characteristics and operation of 25 reservoirs have been included in the model. The total storage capacity of the modeled reservoirs is approximately 26,300 million m^3. A total of 21 headflows and 22 incremental inflows along the reaches are included in the Rio Grande/Rio Bravo WEAP model. The model contains channel loss factors for the river reaches accounting for conveyance, evaporation, evapotranspiration and seepage losses.

Although the model contains inflow data for sixty years, the Rio Grande/Rio Bravo WEAP model has been calibrated for 15 years, from October 1978 to September 1993. This period is selected because most of the basin infrastructure was complete by then and sufficient historical water supply information exists for most of the water demands. In general, two important sets of parameters were used to calibrate the Rio Grande/Rio Bravo WEAP model: the conveyance losses along the streams and the rules governing the release of water from the conservation pools of the dams.

A *Historic* scenario was developed to evaluate the accuracy of the model; results from the model were compared to historical values for reservoir storage and gauged stream flow. During the calibration and validation process, the storage in the international reservoirs Amistad and Falcon were used as indicators to evaluate the performance of the model because: (a) they store the water for each country according to the treaty of 1944; and (b) both reservoirs are influenced by the water management in the entire basin. Two measures were used to evaluate the goodness of fit of the storage in the international reservoirs for each country: the coefficient of efficiency and the coefficient of agreement. These coefficients compare the observed values to the model predicted monthly values. The coefficient of efficiency ranges from minus infinity to 1, with higher values indicating better agreement. The coefficients of efficiency for Mexico and the U.S. are 0.825 and 0.805, respectively; meaning that the mean square error (i.e. the squared differences between the observed and model values) is 17.5% and 19.5% of the variance in the observed data. This level of efficiency coefficient indicates very good performance according to Moriasi et al. (2007). The index of agreement varies from 0 to 1 with higher values indicating a better agreement between the model and the observations. The coefficients of agreement for Mexico and the U.S. are 0.953 and 0.945, respectively; meaning that the mean square error is 4.7% and 5.5% of the potential error. These values indicate that the difference between the observed and predicted values (in fact, the mean square error) is small compared to the variance or the potential error. Both coefficients show that the Rio Grande/Bravo WEAP model is adequately representing the water resource system; the mean square error is less than 20% of the observed variance of the data, and less than 6% of the potential error.

A methodology has been developed in this research to compare and evaluate alternative water management policies. First, a set of performance criteria is selected to evaluate essential or desired qualities required in the water management for each type of water user, the environment or system requirements. Second, results from these performance criteria are summarized using the *Sustainability Index*, which is an index that facilitates the evaluation and comparison of water management policies. Third, Sustainability Indices for several water users are calculated using the *Relative Sustainability Index*, which is an average of the former Sustainability Index weighted by the water demand. Through this method it is possible to evaluate not only the effect of water management policies for individual water users, but also, for groups of water users, the environment, regions and for the whole system.

Five performance criteria are used in the Rio Grande/Rio Bravo: Reliability, Resilience, Vulnerability, Maximum Deficit and Standard Deviation. *Reliability* represents the period of time a user's water demand is fully supplied during the period of simulation. *Resilience* captures the system's capacity to adapt to changing conditions; it is the probability that the system recovers from a period of failure. *Vulnerability* and

Maximum Deficit are the expected value of deficits and the maximum deficit for a user, if they occur. Finally, the *Standard Deviation* criterion is the standard deviation of the water supply the respective water user. The sustainability index is used to summarize these performance criteria.

In this research the *Sustainability Index* proposed by Loucks (1997) was improved, moving from a product of the performance criteria to a geometric average of the performance criteria. This improvement preserves the original characteristics of the Index, but it enhances the content, clarity and flexibility of the sustainability index. One of the main advantages of the *Sustainability Index* is the ability to compare not only individual water users but also environmental or system requirements. The *Relative Sustainability Index* is used to summarize the Sustainability Indices. The *Sustainability Index* is an *Integrated Water Resources Index* that summarizes the results of essential or desired performance criteria rather than an index that address the sustainability of a certain water user. The name of Sustainability Index has been preserved to match the literature on the index.

Initially, eleven water management policies were evaluated in this dissertation. These basic scenarios were divided in two groups, for the upper and lower basin. Scenarios for the upper basin included policies already implemented such as (1) the Mexican PADUA program of water rights buyback in irrigation districts 090 Bajo Rio Conchos and 005 Delicias through the PADUA program, (2) improvements in the infrastructure of DR-005 Delicias due to IBWC Minute 309; and policies proposed such as (3) the Groundwater banking through the *In Lieu* method in DR-005 Delicias and (4) the delivery of environmental flows in the Rio Conchos sub-basin. Scenarios for the lower basin included policies already implemented such as (1) water allocation reduction for U.S. water user along the thirteen Water Master Sections in Texas; and policies proposed such as (2) buyback of water rights and (3) infrastructure improvements in irrigation district 025 Bajo Rio Bravo.

The process of scenario's evaluation was done in two steps (see Figure 9-1). In the first step, each of the basic scenarios or simple combinations of these were evaluated and compared with the *Baseline* scenario. The *Baseline* scenario is the representation of the system before any policy was implemented (before 2004). This scenario is used to quantify, identify and compare the benefits or negative effects of each scenario on water users, the environment or international requirements. The comparison was done using the Sustainability Index and the Relative Sustainability Index. For the upper basin two scenarios produced the most benefits for the system: (1) Scenario I + II, buyback of water rights coupled with groundwater banking in DR-005 Delicias and (2) Scenario III + IV, improvement in infrastructure with water savings delivered in an environmental pattern. For the lower basin two scenarios promoted the most benefits: (1) Scenario III (LRGV) Shared, infrastructure improvements in DR-025 Bajo Rio Bravo and sharing the water savings with Texas Water Master Sections; and (2) Scenario I + III (LRGV), buyback of water right and infrastructure improvements in DR-025 Bajo Rio Bravo.

In the second step, winning scenarios, called *Meta-scenarios*, are compared with the *Current* scenario. The *Current* scenario is the representation of the system after policies were implemented in the basin. Since 2004, three policies have already been implemented in the basin: (1) Scenario I, buyback of water rights through the PADUA program, (2) Scenario II, infrastructure improvement due to Minute 309, and (3) Scenario V (LRGV), reduction in the water allocation for Texas Water Master Sections. *Meta-scenarios* are a combination of policies that consider the policies of the *Current scenario* plus scenarios that were identified in the previous step that increase benefits for the system. Two Meta-scenarios were evaluated and compared with the *Current* scenario: *Meta-scenario A* and *B*.

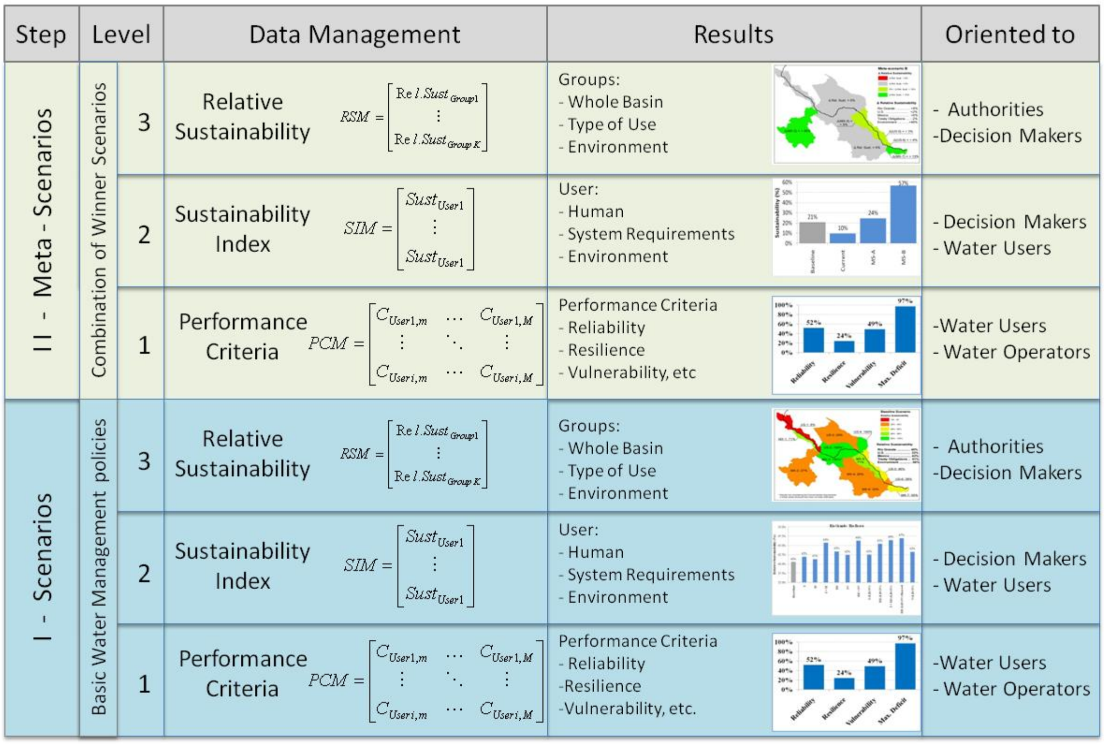


Figure 9-1: Methodology proposed for results' analysis

Meta-scenario A considers Scenario I + II [buyback of water rights plus groundwater banking in DR-005 Delicias], Scenario III + IV [Minute 309 with water savings delivered in an environmental pattern], Scenario I (LRGV) [buyback of water rights in DR-025 Bajo Rio Bravo] and Scenario V (LRGV) [reduction of demand in Texas Water Master Sections from 70% to 62%]. Results from Meta-scenario A show improvements in the water management of the system, with respect to the *Current* scenario. The policies proposed in Meta-scenario A do not affect the water management in the U.S. and Mexico, but it does significantly improve the water supply for environmental purposes, by 46%. The delivery of environmental flows in the Rio Conchos sub-basin does not affect water users in the Rio Conchos sub-basin because: a) water is equitably distributed, maintenance flows are delivered when there is enough water in the reservoirs to fully supply the water users, and drought flows are delivered when shortages are expected; b) the water savings of Minute 309 are delivered in an environmental pattern; and c) there is conjunctive use of surface and groundwater, the groundwater banking policy proposed for the Meoqui aquifer provides a more reliable supply for DR-005. Similarly, the delivery of environmental flows in the Rio Conchos sub-basin does not affect water users in the Lower Rio Grande Valley (LRGV), such as DR-025 Bajo Rio Bravo or the Texas Water Master Sections, because water is captured in the international reservoirs Amistad and Falcon, stored and redistributed according to the necessities of water users in the LRGV. This policy shows a high likelihood that an environmental water management policy might be applied without harming human water users. Water users located in the Rio Conchos sub-basin and the Bajo Rio Bravo regions benefit from this scenario. This is an important result since environmental requirements have mostly been neglected or not considered in this region because they are thought to harm anthropogenic water users. The overall improvements are estimated to be 3%, with respect to the *Current* scenario.

Meta-scenario B is similar to Meta-scenario A with the difference that in Scenario I + II the buyback of water rights is more extensive in order to reduce the irrigated area of DR-005 Delicias from 90,000 ha to 50,000 ha, this reduction might be accomplished by compensating farmers who have water rights that are difficult to supply. Meta-scenario B also includes Scenario III (LRGV) Shared [infrastructure improvements in DR-025 and sharing water savings with Texas Water Master Sections]. Results from Meta-scenario B show significant improvements in the water management of the system, with respect to the *Current* scenario and *Meta-scenario A*. The policies proposed in Meta-scenario B improve water management in the U.S. and Mexico by 2% and 6% according to the *Sustainability by Group Index*, respectively. Results show an increment in the relative sustainability of the environment of 48%. The delivery of environmental flows in the Rio Conchos sub-basin does not affect water users in the Rio Conchos sub-basin for the reasons already explained in Meta-scenario A and because water demands in the Conchos sub-basin have been reduced in order to retire water rights that are difficult to supply. Water users in the LRGV are not affected by environmental flows in the Conchos basin because the environmental flows are captured, stored and redistributed in the international reservoirs Amistad and Falcon. This scenario significantly improves the water supply for environmental purposes. Again, this policy shows the high likelihood that an environmental water management policy might be applied without harming anthropogenic water users. Under this Meta-scenario, water users in located in the Rio Conchos, Bajo Rio Bravo, Amistad-Falcon reach and Lower Rio Grande Valley regions benefit in their water supply. The overall improvement of Meta-scenario B is 8% with respect to the *Current* scenario.

Meta-scenario A could be considered a set of immediate policies that have a high likelihood of improving water management in the basin, mostly for the environment. *Meta-scenario B* could be considered a set short term policies that have a high likelihood of improving water management for the U.S., Mexico, and the environment. Both Meta-scenarios would be implemented by policies that will require decisions from authorities and water users; Meta-scenario A and B are a set of policies suggested by the author; however, the selection and order of these policies can change depending on the decision making process.

In order to assess the water planning and management of the Rio Grande/Rio Bravo, the development and findings of this research have been shared with water users; NGO's; local, state and national water authorities; researchers; academia; and people interested in the Rio Grande/Rio Bravo basin, in both countries. I have participated in several meetings, mostly for three purposes: (1) to learn from the water users, managers, people who operate the system and decision makers that make the regulations and policies; (2) to share and explain the water resources planning model built for the Rio Grande/Rio Bravo basin; and (3) to present the results obtained with the model, and the methodology used to summarize the results.

Two technical sessions (workshops) were conducted in order to explain in detail the construction and algorithms inside the Rio Grande/Rio Bravo water planning model: one at Mexican Institute of Water Technology (IMTA) in Cuernavaca Mexico in March 2009 and the other at the International Boundary and Water Commission (IBWC) in El Paso, Texas in April 2009.

Results of the scenario analysis were presented to several authorities. In June 2009, the results were presented in the IBWC office in Ciudad Juarez, Mexico. Authorities from both countries were presented with and discussed the simulation model and the results obtained. In August 2009 the results of this research were presented to the Rio Bravo Basin Council in Monterrey, Mexico. This organization regulates and establishes the water management policies for the Rio Grande/Rio Bravo on the Mexican side. In October 2009, results were presented to the TCEQ in their central offices at Austin, Texas. Comments and suggestions from Carlos Rubinstein (Commissioner), Stephen Niemeyer (Policy Analyst), Kelly Keel (Water Quality Planning Division) and Ramiro Garcia (Border and South Central Texas Area Director) were received in this meeting. Also, results of scenarios that improve the delivery of environmental requirements were presented to several NGOs, such as World Wildlife Fund, Profauna, The Nature Conservancy, Environmental Defense, among others. Since 2008, I have been part of an international technical group to determine and identify a policy for environmental flows in the Big Bend reach. On December 2009 the World Wildlife Fund organized a field trip on the Rio Conchos with this international group. Research in this area is still in development to determine and propose environmental flows in the Big Bend region.

According to Loucks et al. (1981), a measure of success of any systems' study resides in the answer to the following questions:

(1) *Did the study have a beneficial impact on the planning and decision-making process?* Yes, it did. For the planning process, the model developed in this research will be used as the foundation for the future institutional water planning models of the basin. For the decision making process, water users, scientists, authorities, and decision makers are aware of the potential benefits that are possible to achieve, for whom and where, in the immediate and short term. The current research has balanced the interests of different groups (environmentalist, irrigators, municipalities and authorities) providing a better understanding of the basin.

(2) *Did the results of the study make the debate over the proper choice of alternatives more informed?* Yes, it did. After the campaign of presenting research results (described above), water users, scientists, NGO's, authorities, and decision makers of both countries now know which policies have a high likelihood of improving or worsening the system; the decision making process will be more informed because of the present research.

(3) *Did it introduce competitive alternatives which otherwise could not have been considered?* Yes, it did. For instance, this research provides strategies to reconcile

environmental and anthropogenic water requirements; this research provides evidence that environmental water requirements can be included as an integral part of the basin water management without harming human water users. This is an important result since environmental requirements have tended to be neglected because: (a) they are thought to harm human water users and/or (2) there is no water left for this purpose. This research proves the contrary.

Based on the answers of the previous questions, the current research has been successful in enlightening the water planning and management of the Rio Grande/Rio Bravo basin.

9.3 Conclusions

This dissertation meets the objectives outlined at the beginning of this chapter:

1. A water resources planning model was constructed, calibrated and validated which represents the hydro-physical and regulatory framework of the Rio Grande/Rio Bravo basin, a large scale transboundary basin between the United States and Mexico. The Rio Grande/Rio Bravo WEAP model included 216 demands, 25 reservoirs, and the proper algorithms to allocate water within the U.S., Mexico and among both countries, according to international agreements and national and state regulations. Calibration and validation were performed for a 15 year period. Results from the model testing show a reasonable agreement between the results obtained from the model and the historic records.
2. A methodology that evaluates and compares different scenarios has been defined in this research. The essential or desired qualities for each water user,

environmental or system requirement were evaluated using five performance criteria: Reliability, Resilience, Vulnerability, Maximum Deficit and Standard Deviation. These performance criteria were summarized using the *Sustainability Index*, which is an index that facilitates the evaluation and comparison of water management policies. Furthermore, sustainability indices for several water users were calculated using the *Relative Sustainability Index*, which is an average of the sustainability index weighted by the water demand. Through this methodology it is possible to evaluate not only the effect of water management policies for individual water users, but also, for groups of water users, the environment, regions and for the whole system.

3. The water resources planning model has been used to evaluate different scenarios in the Rio Grande/Rio Bravo basin. Initially, a set of 11 scenarios were evaluated and compared with the *Baseline* scenario (which represents the system before any scenario) in order to identify the benefits and damages for water users, environmental and system requirements. This evaluation helped identify winning policies that improved the water management in the basin. A set of Meta-scenarios (scenarios integrated of winning policies) was evaluated and compared with the *Current* scenario (which represents the system after the scenarios were implemented). Results from the Meta-scenarios showed improvements in the water management for water users, environmental and system requirements, immediately and in the short term.

4. Several actions have been taken to assess the water planning and management in the Rio Grande/Rio Bravo basin including: (1) explaining the algorithms in the model in meetings, trainings and workshops; (2) providing the model with documentation and training on how to use it; (3) presenting results to water users,

authorities, NGO's, academia and all people interested in the water management of the Rio Grande/Rio Bravo; (4) sharing information, findings and knowledge of the basin; (5) promoting discussion about alternative policies to improve the water management in the basin; and (6) being an active participant in the scientific committee to promote environmental flows in the Big Bend area.

5. The methodology applied in the Rio Grande/Rio Bravo can be applied to any other basin, including transboundary basins, for any process of water management evaluation, to determine if the policy or policies proposed improve the water management, by how much, where, and for which performance criteria.

This dissertation defines a methodology to evaluate and compare water management scenarios. The methodology proposed was successfully applied in the Rio Grande/Rio Bravo transboundary basin. This methodology consists of a multistep-multilevel process. Immediate and short term policies are integrated in *Meta-scenario A* and *B*. These policies were compared with the *Current* scenario and showed improvements of 3% and 8%; respectively, with respect of the *Current* water management in the whole basin.

9.4 RECOMMENDATIONS

This dissertation presents a water resources planning model to evaluate several water management scenarios for the Rio Grande/Rio Bravo transboundary basin. The model was calibrated for a 15 year period (Oct/1978 – Sep/1993). Two main parameters were adjusted in the calibration process: the conveyance losses along the streams and the rules governing the releases of water from the conservation pools of the dams. Fixed values were set in the model for conveyance losses along the streams for the whole hydrologic period of analysis; which means that the conveyance losses are the same for the whole season and for all years. Even though this assumption proved adequate for the calibration period (because these values are the mean conveyance losses under normal conditions), further research is needed to determine the conveyance losses as functions of the seasons and the hydrologic conditions (dry, normal or wet).

The objective of this research is to identify policies that can improve water management in the basin for water users of each country, treaty obligations and the environment. The results of this research can be used to suggest policies to authorities, NGOs, water users; however, it was not specifically designed for this purpose. For further insight into the policies and how they can be used to inform decision makers, please contact the author.

9.5 FUTURE WORK

This dissertation is focused on the hydrologic feasibility of the scenarios evaluated; quantifying if there is enough water in the system to apply the proposed scenarios. For all of the scenarios evaluated in this dissertation, except the groundwater banking in irrigation district 005 Delicias, there is enough economic data available to evaluate the cost of each scenario. Further research is needed to determine the cost of implementation and maintenance of the groundwater banking scenario in irrigation district 005 Delicias. Once all the economic data are available, an economic analysis can be performed for the immediate and short term policies proposed in Meta-scenario A and B.

In this dissertation several scenarios were evaluated using a 60 year hydrologic period of analysis, from Oct/1940 to Sep/2000. Even though this period contains several droughts and wet periods, results were obtained for this unique realization of conditions. Because of this, future research is needed to build a stochastic model that allows evaluation of the system under different hydrologic conditions. There is enough hydrologic data in the basin to build a stochastic model that will help evaluate water management under different hydrologic conditions. This will help to identify risks and weaknesses of the proposed Meta-scenarios, as well as confidence interval for the policies.

References

Aldama A. (2008). “Arbitraje a la controversia acera de la Disponibilidad de Aguas Superficiales en la Cuenca del Rio Bravo”. 4 de Abril de 2008.

Amato, C., McKinney, D.C., Ingol-Blanco, E., and Teasley, R.L. "WEAP Hydrology Model Applied: The Rio Conchos Basin," CRWR Online Report 06-12, Rio Grande Project, Center for Research in Water Resources, University of Texas at Austin.

Andreu, J., Capilla, J. and Snachis, E. (1996). “AQUATOOL, a generalized decision-support system for water-resources planning and operational management” *Journal of Hydrology*, Vol.177, 269-291 pp.

Arreguin, F.I., (2010). “La gestión integrada en cuencas transfronterizas,” Segundo coloquio internacional de cuencas sustentables, hacia la COP 16. CONAGUA-SEMANAT, México D.F.

Baran, E. and Coates, D. (2000). “Hydro-biological models for water management in the Meokong River” Hydrologic and Environmental Modeling in the Mekong Basin. pp 328-334.

Bates, B.C., Z.W. Kundzewicz, S. Wu and J.P. Palutikof, Eds. (2008) “Climate Change and Water.” Technical Paper of the Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva, 210 pp.

Biswas, A.K., (1981). Integrated Water Management: Some International Dimensions, Journal of Hydrology, 51: 369-380

Blankinship, D.R. (2005). “When the Rio Grande ceased to flow: effects of Rio Grande mouth closure on estuarine dependant species.” Poster presented at the 135th annual meeting of the American Fisheries Society, Anchorage, AK.

Bogardus, E.S. (1964). “Principles of Cooperation.” Chicago, IL. The cooperation League of the USA.

Boysen, F. (2002). “An overview and evaluation of composite indices of development”. *Journal of Social Indicators Research*. 59: 115-151.

Brandes Company, R.J. (2003a) “Water Availability Modeling for the Río Grande Basin: Naturalized Streamflow Data. Final Report.” Texas Commission on Environmental Quality, Austin, TX.

Brandes Company, R.J. (2003b) “Memo Regarding Channel Losses for the Rio Grande Basin Channel losses in the Rio Grande Basin” Texas Commission on Environmental Quality Project Manager, Rio Grande Water Availability Model. December 15th, 2003.

Brandes Company, R.J. (2004). “Water Availability Modeling for the Río Grande Basin: Water Availability Assessment. Final Report.” Texas Commission on Environmental Quality, Austin, TX.

Brekke, L.D., Kiang, J.E., Olsen, J.R., Pulwarty, R.S., Raff, D.A., Turnipseed, D.P., Webb, R.S., and White, K.D. (2009). “Climate Change and Water Resources management – A Federal Perspective.” U.S. Geological Survey Circular 1331, 65p.

Brizga, S.O., Arthington, A.H., Pusey, B.J., Kennard, M.J., Mackay, S.J., Werren, G.L., Craigie, N.M., and Choy, S.J. (2002). “Benchmarking, a “top-Down” Methodology for Assessing Environmental Flows in Australian Rivers.” *Proc. Of International Conference on Environmental Flows for Rivers*. Cape Town, South Africa: Southern Waters Consulting.

Buras, N. (1963). “Conjunctive Operation of Dams and Aquifers.” *Proc. Amer. Soc. Civil Engineers.* 89(HY6), 111-131.

Burnes, H.S. and Quirk, J.P. (1979). “Appropriative Water rights and the Efficient Allocation of Resources.” The American Economic Review. Vol. 69 (1) 25:37.

Cain, J.R., Dugger, A. Fullerton, D., Purkey, D.R., Sunding, D., and Thomas, G.A. (1998) "An Environmentally Optimal Alternative for the Bay-Delta: A Response to the CALFED Program, " report of the Natural Heritage Institute.

Caballero (2005). “Sociedad de Asociaciones de Usuarios: Unidad Conchos.” Comisión Nacional del Agua. Delicias, Chihuahua, México.

Collado, J. (2002). “Criterios de distribución del agua en la Cuenca del Rio Bravo.” Instituto Mexicano de Tecnología del Agua (IMTA). Cuernavaca, Morelos, México

CILA – Comisión Internacional de Límites y Aguas (2010). “Contabilidad Rio Bravo: Condiciones del Rio Bravo: Almacenamientos en Presas Internacionales.” Ciudad Juárez, México, <http://www.sre.gob.mx/cila/> (Jan. 1, 2010).

CILA – Comisión Internacional de Límites y Aguas (2011). “Almacenamiento en Presas Mexicanas.” <http://www.sre.gob.mx/cila/> (Feb. 15, 2011).

CONAGUA – Comisión Nacional del Agua (2003). “Ficha Técnica: DR 005 Delicias, Chihuahua” México, D.F.

CONAGUA – Comisión Nacional del Agua (2004). “Registro Público de Derechos de Agua.” México, D.F.

CONAGUA – Comisión Nacional del Agua (2005) “Distrito de Riego 026 Bajo Río San Juan.” Subdirección General de Infraestructura Hidroagrícola. Gerencia de Distritos y Unidades de Riego. Gerencia Regional del Río Bravo, Junio 2005.

CONAGUA – Comisión Nacional del Agua (2007). “Diagnostico Hidrológico de la Cuenca del Rio Bravo.” México D.F.

CONAGUA – Comisión Nacional del Agua (2008.a). “Ley de Aguas Nacionales y su Reglamento.” México, D.F.

CONAGUA – Comisión Nacional del Agua (2008.b). “Acuerdo por el que se da a conocer el resultado de los estudios de disponibilidad media anual de las aguas superficiales en la cuenca del Rio Bravo” Diario Oficial de la Federación. 29 de Septiembre de 2008. México D.F.

CONAGUA – Comisión Nacional del Agua (2009). “Estadísticas Agrícolas de los Distritos de Riego. Año Agrícola 2007-2008” Gobierno Federal – Secreatria del Medio Ambiente y Recursos Naturales. Mayo 2009. México D.F.

Coppock, R. H. and Kreith, M. (1992). “California Water Transfers: Gainers and Losers in Two Northern Countries.” University of California, Agricultural Issues Center and Water Resources Center, Davis, California.

Corbridge, J.N. and Wilkinson, C.F. (1985). “The prior appropriation system in western water law: The law viewed through the example of the Rio Grande basin.” Natural Resources Law Center, University of Colorado Law School

CSU – Colorado State University (2011). “MODSIM: operating manual and description.” Fort Collins, CO

CTMMA – Centro del Tercer Mundo para el Manejo del Agua (2001). “Los Consejos de Cuenca en Mexico”. Mexico City.

Czekanski, A. (2005). “Conflict in the Tigris-Euphrates River Basin.”

Danner, C. L., McKinney, D. C., Teasley, R. L., and Sandoval-Solis, S. (2006). “Documentation and Testing of the WEAP Model for the Rio Grande/Bravo Basin.” CRWR Online Report 06-08. University of Texas at Austin. Updated February 2008

De Condappa, D., Chaponniere, A., and Lemoalle, J. (2009) "A Decision-Support Tool for Water Allocation in the Volta Basin," Water International, 34 (2009), pp. 71-87, doi:10.1080/02508060802677861.

Dean, D.J., and Schmidt, J.C., (2011). “The role of feedback mechanisms in historic channel changes of the lower Rio Grande in the Big Bend region,” *J. Geomorphology*, 126, 333-349

Delft Hydraulics (2004). “*RIBASIM: River basin simulation program operating manual and description.”* Netherlands, Delft

DHI – Danish Hydraulic Institute (1997). “MIKE-Basin: operating manual and description.” Denmark, Horsholm.

Dinar, A., and Dinar, S. (2005). "Scarperation: The role of Scarcity in Cooperation among Basin Riparians." International Study Association Convention, Honolulu, Hawaii, Mar 1-5.

Dinar, A., Dinar, S., McCaffrey, S. and McKinney, D.C. (2007). "Bridges over the water." World Scientific Series on Energy and Resource Economics. ISBN-13 978-981-256-893-9

DOI –United States Department of Interior (1922). "Colorado River Compact, 1922" November 24, Santa Fe, New Mexico.

Drewnowski, J. (1974). "On Measuring and Planning the Quality of Life." Mouton, The Hague, pp 19-33

Dudley, T.L., DeLoach, C.J., Lovich, J.E., and Carruthers, R.I. (2000). "Salt cedar invasion of western riparian areas: impacts and new prospects for control." Pages 345–381 in R. E. McCabe and S. E. Loos, editors. Transactions of 65th North American Wildlife and Natural Resources Conference, November 2000, Chicago, Illinois. Wildlife Management Institute, Washington, DC.

Dufournaud, C. (1982). "On the mutually beneficial cooperative scheme: Dynamic change in the payoff Matrix of international river basin schemes." Water Resources Research, 18(4), 764-772

Enriquez-Coyro, E., (1976). "El Tratado entre México y los Estados Unidos de América sobre Ríos Internacionales." Facultad de Ciencias Políticas y Sociales. Universidad Nacional Autónoma de México.

EPA- SEMARNAT [Environmental Protection Agency –Secretaria del Medio Ambiente y Recursos Naturales] (2009). "U.S.-Mexico Environmental Program: Border 2012: Special Edition – Fall 2009" Border 2012 program.

EPSMO - BIOKAVANGO (Environmental Protection and Sustainable Management of the Okavango River Basin – Biodiversity in the Okavango Delta) E-flows Team. (2009). Hydrology report: Data and Models." Report 05-2009. EPSMO/BIOKAVANGO Okavango Basin Environmental Flow Assessment Project, OKACOM, Maun, Botswana.

Esty, D.C., Levy, M., Srebotnjak, T., and Sherbinin, A. (2005). "2005 Environmental Sustainability Index: Benchmarking National Environmental Stewardship." New Haven, Yale Center for Environmental Law and Policy

Everitt, B.L. (1998). Chronology of the spread of tamarisk in the central Rio Grande. Wetlands, Vol. 18, No 4, pp. 658-668.

Fanai, N. and Burn, D. H. (1997). "Reversibility as a sustainability criterion for project selection." *International Journal of Sustainable Development and World Ecology*, 4 (4), 259–273

Fehrenbach, T.R. (2000). “Lone Star: A history of Texas and Texans” Cambridge: Da Capo Press. pp 263

Fipps, G. (2000). “Characterization of Conveyance Losses in Irrigation Distribution Networks in the Lower Rio Grande Valley of Texas: Final Report” US Bureau of Reclamation, Department of Interior. Grant Agreement No. 98-FG-60-10_0

Fipps, G. and Pope, C (2004). “Irrigation district efficiencies and potential water savings in the Lower Rio Grande Valley of Texas”. Texas A&M, College Station, TX

Ganoe. J.T. (1937). “The Desert Land Act in Operation, 1877-1891.” *Agricultural history*, Vol. 11, No. 2, pp. 142-157.

Gastelum, J.R. (2006). “Analisis of water resources management alternatives to improve water allocation on the Conchos Basin during drought situations” PhD. Dissertation. Hydrology and Water Resources Department, University of Arizona

Gastelum, J.R., Valdes, J.B. and Stewart, S. (2009). “A decision support system to improve water resources management in the Conchos Basin,” Water Resources Manage, 23:1519-1548.

Georgakakos, A.P. (2007). “Decision Support Systems for Integrated Water Resources Management with an Application to the Nile Basin.” in Topics on System Analysis and Integrated Water Resources Management by Castelletti, A. and Soncini-Sessa, R. Elsevire

Georgakakos, A.P., and Martin, Q.W. (eds) (1996). “An international review of decision support systems in river basin operation.” Proceeding of the Fifth Water Resources Operation Management Workshop, March, Arlington, VA. ASCE

Gilmore, A., Magee, T., Fulp, T., and Strzepek, K. (2000) “Multiobjective Optimization of the Colorado River,” Joint Conference on Water Resources Engineering and Water Resources Planning and Management, ASCE New York, NY.

Giordano, M.A., and Wolf, A.T. (2002). “Atlas of International Freshwater Agreements. The World’s International Freshwater Agreements.” United Nations Environment Programme. <http://www.transboundarywaters.orst.edu/publications/atlas/index.html>

Giorgi, F. and Mearns, L. O. (2002). “Calculation of Average, Uncertainty Range, and Reliability of Regional Climate Changes from AOGCM Simulations via the Reliability Ensemble Averaging (REA) Method.” *Journal of Climate*, Vol. 15, Issue 10, pp. 1141-1158

Gomez, J.F., Mejia, R. and Gutierrez, A. (2005). “Estudio de modelos distribuidos para la simulación del escurrimiento en cuencas. Aplicación a la cuenca del Rio Conchos, afluente del rio Bravo: Informe Final,” Instituto Mexicano de Tecnología del Agua. Proyecto SEMARNAT-2002-C01-0569.A3

Gwartney, J., R. Lawson and Block, W. (1996). “Economic Freedom of the World (1975–1995).” Free Market Foundation, Johannesburg, pp. 1–46

GWP – Global Water Partnership (200). “Integrated Water Resources Management.” Tac Background, Papers No. 4, Stockholm, Sweden, GWP.

Hajkowicz, S. (2005). “Multi-attributed environmental index construction.” *Journal of Ecological Economics*. 57 (2006) 122-139.

Hall, J. and Murphy, C. (2010). "Vulnerability Analysis of Future Public Water Supply Under Changing Climate Conditions: A Study of the Moy Catchment, Western Ireland," Water Resources Management, Volume 24, Number 13, 3527-3545

Harmon, J. (1895). “Opinion of U.S. Attorney General Judson Harmon” 21Op. Att’y Gen. 274.

Hashimoto, T., Stedinger, J. R., and Loucks, D. P. (1982). “Reliability, resiliency and vulnerability criteria for water resource system performance evaluation.” Water Resources Research Journal, 18 (1), 14-20.

Hatch (1878). “El Paso Troubles.” House Document. Washington Gov. Printing Office, 1878. 45th Congress., 2nd session, Document 84.

Hopkins, M. (1991). “Human development revisited: A new UNDP report.” World Development 19, pp. 1469-1473

Howmiller, R. P., and Scott, M. A. (1977). “Oligochaetes as indicators of pollution.” *Proc. 15th Annual Waste Conference*, Purdue University, West Lafayette, IN.

Humboldt, A. (1966). “Ensayo Político sobre el Reino de la Nueva España.” Porrua Ed. pp. 197. Mexico City.

Hutchins, W.A., Ellis, H.H., and DeBraal, J.P. (2004). “Water rights laws in the nineteen western states,” Vol. 1, The Lawbook Exchange, LTD. U.S. Department of Agriculture

HydroLogics Inc. (2009). “User manual for OASIS with OCL.” Portland. OR. <http://www.HydroLogicss.net>

IBWC - International Boundary and Water Commission (1848). “Treaty between the United States of America and the Mexican Republic.” International Boundary and Water Commission, February 2. Mexico City, Mexico.

IBWC - International Boundary and Water Commission (1906). “Convention between the United States and Mexico. Equitable Distribution of Waters of the Rio Grande.” International Boundary and Water Commission, May 21. El Paso, TX.

IBWC - International Boundary and Water Commission (1944). “Treaty Between the United States and Mexico. Utilization of waters of the Colorado and Tijuana Rivers and of the Rio Grande” International Boundary and Water Commission (IBWC). February 3. Washington D.C.

IBWC - International Boundary and Water Commission (1946). "Runoff of the Conchos River at Ojinaga under Present and Future Conditions" International Boundary and Water Commission (IBWC). April 30, 1946. Ciudad Juarez, Chihuahua, Mexico.

IBWC - International Boundary and Water Commission (1963). "Convention Between the United States of America and Mexico. Boundary: Solution of the Problem of the Chamizal". International Boundary and Water Commission (IBWC), August 29th. Mexico City. Mexico.

IBWC - International Boundary and Water Commission (1969). "Minute 234". International Boundary and Water Commission (IBWC), December 2nd. Ciudad Juarez, Chihuahua, Mexico.

IBWC - International Boundary and Water Commission (1970). "Treaty to resolve the pending boundary differences and maintain the Rio Grande and Rio Colorado as the international boundary". International Boundary and Water Commission (IBWC), November 23rd. Mexico City, Mexico.

IBWC - International Boundary and Water Commission (2001). "Minute 307". International Boundary and Water Commission (IBWC), March 16th. Washington D.C.

IBWC - International Boundary and Water Commission (2002). "Minute 308". International Boundary and Water Commission (IBWC), June 28th. Ciudad Juarez, Chihuahua, Mexico.

IBWC - International Boundary and Water Commission (2003). "Minute 309". International Boundary and Water Commission (IBWC). July 3rd. El Paso, Texas.

IBWC - International Boundary and Water Commission (2005). "Procedimiento de cálculo para la contabilidad de las aguas en el Rio Bravo. Criterio para calcular las pérdidas de las aportaciones de los afluentes mexicanos al Rio Bravo asociadas con las transferencias de agua de las presas internacionales". February 2005. Ciudad Juarez, Chihuahua, Mexico.

IBWC - International Boundary and Water Commission (2007). "México delivers water to the United States to Fulfill Treaty Obligations. "Press Release, October 12th, El Paso, Texas.

IBWC - International Boundary and Water Commission (2008). "Regional Assessment of water quality, Rio Grande basin". Texas Clean Rivers Program, El Paso, TX.

IBWC - International Boundary and Water Commission (2009). "Rio Grande Historical Mean Daily Discharge Data." <http://www.ibwc.state.gov/Water_Data/histflo1.htm> (Dec. 31, 2009).

IBWC - International Boundary and Water Commission (2010). “History of the International Boundary and Water Commission.” <http://www.ibwc.gov/About_Us/history.html> (April 30, 2010).

IBWC - International Boundary and Water Commission (2011). “Amistad-Falcon Ownership Trends 1996-present.” <http://www.ibwc.gov/Water_Data/Reports/RG_Storage_Conditions.htm#> (February 15th, 2011).

IBWC - International Boundary and Water Commission DEIS – Draft Environmental Impact Statement (2003a). “River Management Alternatives for the Rio Grande Canalization Project (RGCP) Section 3.” International Boundary and Water Commission (IBWC), El Paso, TX.

IBWC - International Boundary and Water Commission DEIS – Draft Environmental Impact Statement (2003b). “River Management Alternatives for the Rio Grande Canalization Project (RGCP) Section 6.” International Boundary and Water Commission (IBWC), El Paso, TX.

ILA – International Law Association (1966). “Rules on the Uses of the Water of International Rivers”, Helsinki, Finland.

Ingol-Blanco, E. and McKinney, D.C. (2008). “Hydrologic Model for the Rio Conchos Basin: Calibration and Validation” CRWR Online Report 08-9. University of Texas at Austin

Ingol-Blanco, E. and McKinney, D.C. (2009). “Modelo de calidad del agua para la cuenca del Rio Bravo/Grande: Reporte Final” Collaborative research project Instituto Mexicano de Tecnología del Agua – The University of Texas at Austin.

IPCC - Intergovernmental Panel on Climate Change. (2007a). “Climate Change 2007: Synthesis Report.” Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Pachauri, R.K and Reisinger, A. (eds.)]. IPCC, Geneva, Switzerland, 104 pp.

IPCC - Intergovernmental Panel on Climate Change. (2007b). “Summary for Policymakers in Climate Change 2007: Impacts, Adaptation and Vulnerability.” Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, UK, 7-22.

IUCN – The International Union for Conservation of Nature. (1980). “The World Conservation Strategy: living resource conservation for sustainable development.” The International Union for Conservation of Nature-United Nations Environment Program-World Wildlife Fund, Gland, Switzerland.

Johnson, W.V. (1994). "Accounting for Water Supply and Demand: An Application of Computer Program WEAP to the Upper Chattahoochee River Basin, Georgia," Training Document No. 34, Hydrologic Engineering Center, US Army Corps of Engineers

Klemes, V., Srikanthan, R., and McMahon T.A. (1981). "Long-memory flow models in reservoir analysis: what is their practical value?" *Water Resources Research* 17 (3), 737-751.

KWB – Kern Water Bank (2008). "Recharge and Recovery-Infrastructure Development." Kern Water Bank Authority, Bakersfield, CA. <http://www.kwb.org/main.htm> (Mar. 3, 2010)

Labadie, J.W., and Sullivan, C.H. (1986) "Computerized Decision Support Systems for Water Managers." *Journal of Water Resources Planning and Management*. Vol. 112, pp. 299-307

Legates, D.R., and McCabe, G.J. (1999). "Evaluating the use of "goodness-of-fit" measures in hydrologic and hydroclimatic model validation." *Water Resources Research j.,* Vol. 35, No. 1. Pages 233-241.

Lence, B.J., Furst, J., and Matheson, S. (1997). "Distributive fairness as a criterion for sustainability evaluative measures and application to project selection." *International Journal of Sustainable Development and World Ecology* 4 (4), 245–258

Loucks, D.P. (1997). "Quantifying trends in system sustainability." *Hydrological Science Journal*, 42(4):513-530.

Loucks D.P., and Da Costa, J.R. (eds.) 1991. "Decision Support Systems." NATO Series G. Vol 26. Berlin, Springer-Verlag.

Loucks, D.P., Stedinger, J.R., and Haith, D.A. (1981). "Water Resource Systems Planning and Analysis." Prentice Hall, Englewood Cliffs, New Jersey.

Loucks D. P. and van Beek, E. (2005). "Water Resources Systems Planning and Management." United Nations Educational, Scientific and Cultural Organization (UNESCO), Paris, France.

LST – Legislature of the State of Texas (2007). "Senate Bill 3: An Act relating to the development, management and preservation of the water resources of the state," May 58th, Austin, TX

Lupu, Y. (2002). "Georgetown International Environmental Law: Review: Law and the Waters of the Euphrates and Tigris." Georgetown University Law Center, pp. 350-366

Maass, A., Hufschmidt, M.M., Dorfman, R., Thomas, H.A., Marglin, S.A. and Maskev, G. (1966). "Design of Water Resources Systems: New techniques for Relating

Economic Objectives, Engineering Analysis and Governmental Planning." Harvard University Press, Cambridge, Massachusetts.

Matalas, N. C., and Fiering, M. B. (1977). "Water Resources Systems Planning in Climate, Climate Change, and Water Supply." National Academy of Sciences, Washington D.C.

Mathis, M.L., Haut, R., Matisoff, D., and Richardson, R. (2006). "The economic value of water and ecosystem preservation Part 2: Freshwater Inflows from the Rio Grande." Houston Advanced Research Center, September 2006

Mauser, W. and Ludwig, R. (2002). "GLOWA Danube: A research concept to develop integrative techniques, scenarios and strategies regarding global changes of the water cycle." in Climate Change: Implications for the Hydrological Cycle and for water Management. Beniston, M. (ed.) 171-188

McCartney, M.P. (2007). "Decision Support System for large dam planning and operation in Africa" Colombo, Sri Lanka: International Water Management Institute. 47p. (IWMI Working Paper 119)

McMahon T. A., Adeloye. A. J., and Sen-Lin, Z. (2006). "Understanding performance measures of reservoirs." *Journal of Hydrology*, 324 (2006) 359-382.

McPhee, J. and W. Yeh (2004). "Multiobjective optimization for sustainable groundwater management in semiarid regions." *J. Water Resour. Planning and Management*, 130(6), 490-497.

Mehta, V., Purkey, D., Young, C., Joyce, B., and Yates, D. "Application of the Water Evaluation and Planning (WEAP) System for Integrated Hydrologic and Scenario-based Water Resources Systems Modeling in the Western Sierra Nevada," American Geophysical Union, Fall Meeting.

Mendoza, V. M., Villanuave, E. E., and Adem, J. (1997). "Vulnerability of basins and watersheds in Mexico to global climate change." *Climate Research Journal,* Vol. 9: 139-145, 1997

Milbrink, G. (1983). "An improved environmental index based on the relative abundance of oligochaete species." *Journal of Hydrobiology*, Vol. 102, Number 2/June. ISSN 0018-8158

Mills, A. and Follett, W. (1898). "Report on the equitable distribution of the waters of the Rio Grande." Senate Document. Washington D.C.

Moriasi, D. N., J. G. Arnold, M. W. Van Liew, R. L. Bingner, R. D. Harmel, T. L. Veith (2007). Model Evaluation Guidelines for Systematic Quantification of Accuracy in Watershed simulations. Trans. American Society of Agricultural and Biological Engineers 50(3): 885−900.

Moy, W.S., Cohon, J.L., and Revelle, C.S. (1986). “A programming model for analysis of reliability, resilience and vulnerability of a water supply reservoir.” *J. Water Resources Research,* 22 (4), 2135–2141.

MRC – Mekong River Commission (2004). “Decision Support Framework. Water Utilization Project Component A: Final Report.” Vol. 11: Technical Reference Report. DSF 620 SWAT and IQQM Models.

Nash, J.E. and Sutcliffe, J.V. (1970). “River flow forecasting through conceptual models Part I - A discussion of principles.” *Journal of Hydrology*, 10, 282-290.

NADB – North American Development Bank (2010.a). “Summary of completed projects” NADB Quarterly Report.

NADB – North American Development Bank (2010.b). “Summary of project implementation activities” NADB Quarterly Report.

NBI – Nile Basin Initiative (2002). “Headquarters Agreement between the Government of the Republic of Uganda and the Nile Basin Initiative”, Kampala, Uganda. Nov. 4th.

NHI – Natural Heritage Institute (2001). “Designing successful groundwater banking programs in the central valley: Lessons from experience” San Francisco, CA.

NHI - Natural Heritage Institute (2006b). “Water Management Scenarios for the Rio Grande/Bravo basin from the Rio Conchos to the Gulf.” San Francisco, CA.

Nieuwkamer, R.L.J. (1995) “Decision Support for River Management.” Technische Universiteit Twente.

Nile (1929). “Exchange of Notes between the UK and Egypt in regard to Use of the Waters of the River Nile for Irrigation Purposes” Cairo, Egypt, May 7th, 93 LNTS p.44

Nile (1959). “Agreement between the United Arab Republic and the Republic of Sudan for the Full Utilization of the Nile Waters” Cairo, Egypt, Nov 8th, 453 UNTS p.51

Oppenheim, M.A. (1928). “International Law, A Treatise” 4th Edition, Longmans Green and Co. pp 249, 252:254, and 381.

Orive-Alba, Adolfo (1945). “Informe técnico sobre el tratado internacional de aguas presentado ante el H. Senado mexicano” Comisión Nacional de Irrigación. Septiembre, México D.F...

Palmer, R.N. (2010). “Basic Introduction to STELLA II.” Online. Available <http://www.ce.washington.edu/pub/palmer/CEE576/StellaIntro.PDF> Accessed: Dec. 31st, 2010

Palmer, W. C. (1965). "Meteorological Drought", Research Paper 45, Weather Bureau, U.S. Dept. of Commerce, Washington, D. C., USA, 58 pp

Paredes, J., Andreu, J., and Solera, A. (2010). "A decision support system for water quality issues in the Manzanares River (Madrid, Spain)" *J. Science of the Total Environment*, 408 2576-2589

Patiño-Gomez, C., McKinney, D.C., and Maidment, D.R. (2007). "Sharing Water Resources Data in the Bi-National Rio Grande/Bravo Basin." *J. Water Resour. Planning and Management*, 133(5), 416-426.

Pulido-Velazquez, M., Andreu, J., and Sahuquillo, A. (2006). "Economic Optimization of Conjunctive Use of Surface Water and Groundwater at the Basin Scale." *Water Resources. Planning and Management Journal,* 132(6), 454-467.

Purkey, D. R., Huber-Lee, A., Yates, D., Hanemann, M., and Herrod-Julius, S. (2007). "Integrating a Climate Change Assessment Tool into Stakeholder-Driven Water Management Decision-Making Processes in California." *J. Water Resources Management*, 21(1), 315-329

Purkey, D., Joyce, B., Vicuna, S., Hanemann, M., Dale, L., Yates, D., and Dracup, J. (2008) "Robust analysis of future climate change impacts on water for agriculture and other sectors: a case study in the Sacramento Valley," *Climatic Change*, (87) 2008, pp 109-122, doi:10.1007/s10584-007-9375-8.

Purkey, D. and Escobar, M. "Climate Change, Glaciers, and Water Management in the Rio Santa Watershed, Peru," American Geophysical Union, Fall Meeting.

Ransmeier, J.S. (1942). "The Tennessee Valley Authority; a case study in the economics of multiple purpose stream planning." The Vanderbilt University Press, Nashville.

Raskin, P., Hansen, E., Zhu, Z., and Stavisky, D. "Simulation of Water Supply and Demand in the Aral Sea Region," *Water International*, 17 (1992), pp. 55-67.

Raskin, P., Seiber, J, and Heber-Lee, A. (2001). "Water Evaluation and Planning System: User guide for WEAP 21." Tellus Institute, Boston, MA.

Read, L.K. and McKinney, D.C. (2010). Addressing water availability and climate change issues in the Cordillera Blanca, Peru through technical analysis and community building strategies," CRWR Online Report 2010-09. University of Texas at Austin.

Reining, Y., Behrens, J and E. Charles (1999). "Using simulation to develop a Conjunctive use policy: The Salt River project experience." *Proc. Amer. Soc. Civil Engineers,* 102, 177.

Rogers, P. (1969). "A game theory approach to the problem of international river basins." *Water Resources Research,* 5(4), 749-760.

Rogers, P. (1991). "International River Basins: Pervasive Unidirectional Externalities." Italy: Universita di Siena

Rogers, P. (1993). "The value of Cooperation in resolving international river basin disputes." Natural Resources Forum, 15, 117-131

SADC – Southern African Development Community (2000). “Protocol on Shared Watercourse in the Southern African Development Community.” Botswana, Lesotho, Malawi, Mauritius, Namibia, South Africa, Swaziland Tanzania, Zambia and Zimbabwe.

Sagar, A. D. and Najam, A. (1998). “The human development index: a critical review.” *Ecological Economics Journal*, 25, 249-264

SAGARPA - Secretaria de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación (2003). “Reglas de Operación del Programa de Adquisición de Derechos de Uso del Agua.” Diario Oficial de la Federación, 12 Agosto del 2003.

SAGARPA - Secretaria de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación (2005). “Beneficiarios 2004.” <http://www.sagarpa.gob.mx/v1/subagri/info/sust/agua/padua/ben_padua04.swf> (Mar. 3, 2010).

SAGARPA - Secretaria de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación (2006). “Avances del Programa PADUA.” México, D.F.

SAGARPA - Secretaria de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación (2007). “Beneficiarios 2005-2006.” México, D.F.

SAGARPA-FAO, (2005), “Informe de Evaluación Nacional. Programa PADUA 2004.” Mexico, D.F.

Sainz, P. (1989). “An index of social welfare, Towards a New Way to Measure Development.” Report on the international meeting on more effective development indicators. July 31 - August 3, pp 156-160.

Samaniego-López, M.A. (2004) “Ríos Internacionales entre México y Estados Unidos. Los tratados de 1906 y 1944.” PhD. Dissertation, Colegio de México, Centro de Estudios Históricos, México City, México.

Salewicz, K.A., (1991). “Development of a support system for managing large international rivers.” Terminal Report for the Project No. FP/5202-81-06(2764). International Institute for Applied Systems Analysis, Laxenburg, Austria

Salewicz, K.A. and Nakayama, M. (2009). “Development of a web-based decision support system (DSS) for managing large international rivers,” *Journal Global Environmental Change*, Vol. 14, 25-37

Sandoval-Solis, S. (2005). “Surface Water Availability Model for the San Juan Basin,” MS Thesis. Instituto Politécnico Nacional. Mexico City, Mexico.

Sandoval-Solis, S. (2009.a). “Integrated water resources management for the Rio Verde basin” Research Project. Instituto Politécnico Nacional. Mexico City, Mexico.

Sandoval-Solis, S. (2009.b). “Water management model for the Rio Copalita” Flagship project. Instituto Politécnico Nacional. Mexico City, Mexico.

Sandoval-Solis, S. and McKinney, D. C. (2009). "Hydrological Feasibility of Environmental Flows in The Rio Grande/Bravo Basin." *Proc., World Environmental and Water Resources Congress 2009, ASCE,* Kansas City, MO.

Sandoval-Solis, S., Reith, B. and McKinney, D.C. (2010). "Hydrologic Analysis before and after reservoir alteration at the Big Bend Region, Rio Grande/Rio Bravo." CRWR Online Report 2010-06. University of Texas at Austin.

Sandoval-Solis, S., and McKinney, D.C. (2010). "Environmental Restoration flows for the Bi-National Peace Park at Big Bend." Proc. Graduate Student Workshop on International / Transboundary Water. University of California, Riverside.

Sandoval-Solis, S. and McKinney, D. C. (2011). "Risk analysis of the 1944 Treaty between the United States and Mexico for the Rio Grande/Bravo Basin." *Proc., World Environmental and Water Resources Congress 2011, ASCE,* Palm Spring, CA.

Savoskul, O. S., Chevnina, E.V., Perziger, F.I., Vasilina, L.Y., Baburin,V.L., Danshin, A.I., Matyakubov, B., and Murakaev, R.R. "Water, Climate, Food, and Environment in the Syr Darya Basin," contribution to the ADAPT Project.

Schuster, R.J. (1989). "The Colorado River Simulation System." *Hydraulic Engineering*, ASCE, New York, NY, M. Ports, ed, 473-478.

Schmidt, J.C., Everitt, B.L. and Richard, G. A. (2003). Hydrology and geomorphology of the Rio Grande and implications for river rehabilitation. Special Publications. Aquatic Fauna of the Northern Chihuahuan Desert. Sul Ross State University, Alpine, Texas.

SEI – Stockholm Environment Institute (2010) "WEAP – Water Evaluation Analysis System," <http://www.weap21.org > (July 10, 2010).

SEMARNAP – Secretaria de Medio Ambiente, Recursos Naturales y Pesca (1995). Decreto mediante el cual se otorgan facilidades administrativas y se condonan contribuciones a los usuarios de aguas nacionales y sus bienes públicos inherentes que realicen actividades de carácter agrícola, silvícola, pecuario y acuícola. Diario Oficial de la Federación, 11 de Octubre de 1995.

SEMARNAT – Secretaria de Medio Ambiente y Recursos Naturales (2002). Decreto mediante el cual se otorgan facilidades administrativas para la regularización de usuarios de aguas nacionales que realicen actividades de carácter agrícola. Diario Oficial de la Federación, 4 de Febrero de 2002.

SEMARNAT - Secretaria de Medio Ambiente y Recursos Naturales (2004). "Estadísticas del Agua en México." Comisión Nacional del Agua. Sistema Unificado de Información Básica del Agua, México D.F.

Simonovic, S. P. (1998). "Sustainable Reservoir Development and Management." International Association Hydrological Sciences Publ. No. 251

Simonovic, S. P. (1999). “Decision Support System for Flood Management in the Red River basin,” Canadian Water Resources Journal, Vol. 24, No. 3, 203-223

Slottje, D.J. (1991). “Measuring the quality of life across countries.” *Review of Economics and Statistics Journal*, Vol. 73, No. 4, pp. 684-693

Sorisi, C. (2006) "Public Participation and Institutional Analysis Assessing the Role of System Dynamic Models in the Case Study of the Upper Guadiana Basin in Spain," MS thesis, University of Oxford, UK.

Stewart, S., Valdés, J., Gastélum, J., Brookshire, D., Aparicio, J., Hidalgo, J., and Velazco, I. (2004) “A decision support system for demand management in the Rio Conchos Basin, México.” Proc. of hydrology: science & practice for the 21st Century. British Hydrological Society II:487–494

SWSD – Semitropic Water Storage District (2004). “Semitropic Groundwater Banking Program”. Groundwater Banking, Wasco, CA. <http://www.semitropic.com/index.htm> (Mar. 3, 2010).

Tate, D.E., (2002). “Bringing technology to the table: Computer modeling, dispute resolution and the Rio Grande” MS report, The University of Texas at Austin. Austin, TX

Tate, E., Dhlamini, S., and Meigh, J. (2002). “Southern Africa FRIEND phase 2. Water resources and climate change on Swaziland: a grid based modeling approach.” CEII, Wallingford

TCEQ - Texas Commission on Environmental Quality (1938). “Rio Grande Compact.” Texas Water Code, Title 3, Chapter 41.

TCEQ – Texas Commission on Environmental Quality (2003). “Memo Regarding Channel Losses for the Rio Grande Basin.” December 15, Austin, TX.

TCEQ – Texas Commission on Environmental Quality (2005a). “Rio Grande Water Master Program.” July 17, Austin, TX.

TCEQ - Texas Commission on Environmental Quality (2005b) “Water Availability Models.”<http://www.tceq.state.tx.U.S./permitting/water_supply/water_rights/wam.html>.

TCEQ – Texas Commission on Environmental Quality (2006). “Operation of the Rio Grande: Allocation and Distribution of Waters” Texas Administrative Code Title 30: Environmental Quality, Part 1, Chapter 303, Subchapter C. Austin, TX.

TCEQ – Texas Commission on Environmental Quality (2007). “Water Availability models: Rio Grande Basin”. Austin, TX

Teasley, R.L. (2009). “Evaluating water resource management in transboundary river basins using cooperative game theory: the Rio Grande/Bravo basin.” Dissertation, The University of Texas at Austin, Austin, TX

Teasley, R.L. and McKinney, D.C. (2011). "Calculating the benefits of transboundary river basin cooperation: The Syr Darya Basin" Journal of Water Resources Planning and Management. doi:10.1061/(ASCE)WR.1943-5452.0000141

Tharme, R.E. and King, J.M. (1998). "Development of the Building Block Methodology for in stream flow assessments, and supporting research on the effects of different magnitude flows on riverine ecosystems." *Water Research Commission Report No.* 576/1/98. 452 pp.

TWDB – Texas Water Development Board (2001). "Region M, Rio Grande Regional Water Plan 2001-2006." Austin TX.

TWDB – Texas Water Development Board (2010.a). "Region E, Far West Texas Water Plan: Executive Summary." Austin TX.

TWDB – Texas Water Development Board (2010.b). "Region J, Plateau Texas Water Plan: Executive Summary." Austin TX.

TWDB – Texas Water Development Board (2010.c). "Region M, Rio Grande Regional Water Plan: Executive Summary." Austin TX.

USBR - United States Bureau of Reclamation (1949). "Reclamation Manual: Basin and Project Development." Vol. 3, Denver, Colorado.

USBR - United States Bureau of Reclamation (2006). "Supplemental Information Report: All-American Canal Lining Project." January 12th.

USBR - United States Bureau of Reclamation (2010). "Boulder Canyon Project – All American Canal System." January 05th, Department of Interior

USC – United States Congress (1973). "The Endangered Species Act of 1973" Senate and House of Representatives of the United States of America

UN - United Nations (1978). Register of International Rivers. Oxford, UK. Pergamon Press.

UN - United Nations (1997). "Convention Convention on the Law of the Non-navigational Uses of International Watercourses." General Assembly of the United Nations. May 21st.

UNECE – United Nations Economic Commission for Europe (1991). "Convention on Environmental Impact Assessment in a Transboundary Context." February 25th, Helsinki, Finland.

UNECE – United Nations Economic Commission for Europe (1992). "Convention on the Protection and Use of Transboundary Watercourses and International Lakes." March 17th, Helsinki, Finland.

Vallarta, I.L. (1892). "Dictámenes sobre el abuso de las aguas de los Ríos Bravo, Colorado y sus afluentes" Secretaria de Fomento

Vargas, S., Mollard, E., Romero, R., and Murillo, D. (2004). “Evaluación Social de los escenarios de manejo del agua superficial en la cuenca Lerma-Chapala: Informe Final,” Instituto Mexicano de Tecnología del Agua, Proyecto CPO322

Viers, J.H., Epke, G., Yarnell, S. and Mount, J. (2010) "Characterization of the Unregulated Spring Snowmelt Recession in the Sierra Nevada, California, and Potential Changes with Regional Climate Warming," American Geophysical Union, Fall Meeting.

Vigerstol, K. (2002). “Drought Management in Mexico’s Rio Bravo Basin” MS thesis, University of Washington, Seattle, WA

Von Neumann, J., and Morgenstern, O. (1974). “Theory of Games and Economic Behavior.” Princeton University press, Princeton, N.J.

Wagner, A. I. and J. E. Vaquero (2002). “Modelo dinámico para el análisis de escenarios prospectivos en la Cuenca del Río Conchos.” Instituto Mexicano de Tecnología del Agua (IMTA). Jiutepec, Morelos, México.

WBC – World Birding Center (2011) – “Rio Grande Valley”. <http://www.worldbirdingcenter.org/index.html> Last visited Feb. 1st, 2011

WCED – World Commission on Environment and Development (1987). “Our Common Future. The Brundtland Report.” Oxford University Press, Oxford, UK

WHO - World Health Organization (2009). “Summary and policy implications Vision 2030: the resilience of water supply and sanitation in the face of climate change.” WHO Press. ISBN: 978241598422

William, D.C. (2004). “Lone Star Rising: The revolutionary Birth of the Texas Republic” Free Press. ISBN 0-684-86510-6

Willmott, C.J., Ackleson, S.G., Davis, R.E., Feddema, J.J., Klink, K.M., Legates, D.R., O’Donnell, J., and Rowe, C.M. (1985). “Statistics for the evaluation and comparison of models.” *Geophysics Research Journal*, 90, 8995-9005.

Wolf, A.T. (2002). “Atlas of International Freshwater Agreements. Thematic Maps: Visualizing Spatial Variability and Shared Benefits” United Nations Environment Programme. <http://www.transboundarywaters.orst.edu/publications/atlas/index.html>

Wurbs, R. (2005). “Water Rights Analysis Package (WRAP): modeling system reference manual.” Texas A&M, College Station TX.

WWD – Westland’s Water District (2004). “Groundwater Management Program.” <http://www.westlandswater.org/> (Mar. 3, 2010)

WWF - World Wildlife Fund (2006). “Conclusions from the Building Block Method specialist work session Rio Conchos.” February 27 - March 1, 2006. Chihuahuan Desert Program Office, Chihuahua City, Mexico

WWF - World Wildlife Fund (2007). “World’s top 10 rivers at risk” WWF International. Gland, Switzerland.

WWF - World Wildlife Fund (2008). “Environmental Flow Assessment for the Rio Conchos” Chihuahuan Desert Program Office, Chihuahua City, Mexico

Yates, D., Sieber, J., Purkey, D.R., and Huber-Lee, A. (2005a). “WEAP21-A Demand, Priority, and Preference Driven Water Planning Model: Part 1, Model Characteristics." *Water International*, 30, 487-500.

Yates, D., Sieber, J., Purkey, D.R., and Huber-Lee, A. (2005b). “WEAP21-A Demand, Priority, and Preference Driven Water Planning Model: Part 2, Aiding Freshwater Ecosystem Service Evaluation." *Water International*, 30, 501-512.

Yates, D., Purkey, D., Sieber, J., Huber-Lee, A., Galbraith, H., West, J., Herrod-Julius, S., Young, C., Joyce, B., and Rayej, M. (2009) "Climate Driven Water Resources Model of the Sacramento Basin, California," ASCE Journal of Water Resources Planning and Management, (2009) 135, pp. 303-313, doi:10.1061/(ASCE)0733-9496(2009)135:5(303).

Yoskowitz, D.W. (1999). “Spot market for water along the Texas Rio Grande: opportunities for water management” *Natural Resources Journal*, Vol 39, 345-355

Zagona, E.A., Terrance J.F., Morgan, H. G. and Shane, R.M. (1998). “RiverWare: A General River and Reservoir Modeling Environment.” Proceedings of the First Federal Interagency Hydrologic Modeling Conference, Las Vegas, NV.

Zatarain, F., Lazaro, P., de Leon, B., Robles, B., Fuentes, C., Montesillo, J.L., and Reyes, R. (2005). “Posibilidad de reconversión productiva del distrito de riego 025 Bajo Rio Bravvo, Tamaulipas” Anuario, IMTA.

Zongxue, X., Jinno, K., Kawanura, A., Takesaki, S., and Ito, K. (1998). “Performance risk analysis for Fukuoka water supply system.” *Water Resources Management Journal*. 12, 13–30

VITA

Samuel Sandoval Solis was born in Mexico City, Mexico on August 20th, 1980, the only son of Jesus Jorge Sandoval y Sanchez and Alicia Solano Audeves. Mr. Sandoval has one older sister, Georgina. After graduating from high school, he started his undergraduate studies in Civil Engineering at Instituto Politecnico Nacional (IPN) in Mexico City. Mr. Sandoval received his Bachelor of Engineering degree from IPN in June, 2003. In January 2003, he started his graduate studies at IPN; he received his Master's of Science in Hydraulics with honors in December 2005 for the thesis "Surface Water Availability Model for the San Juan Basin". He also was awarded first of his class during his Master's of Science studies. In 2006 he was awarded with a scholarship from the Mexican Council of Science and Technology (CONACYT from his acronym in Spanish) to make his doctoral studies in the program of Civil, Environmental and Water Resources Engineering at The University of Texas at Austin, where he moved with his wife Silvia in fall 2006. Since then, he has focused his research in the Rio Grande/Rio Bravo basin, a transboundary basin between the United States and Mexico. In particular, Mr. Sandoval has done extensive research in finding policies that would improve the water management in the basin for water users, international obligations and the environment. The author has accepted a Cooperative Extension Specialist position in the department of Land, Air and Water Resources at University of California, Davis, where he will expand his area of expertise to California.

Permanent Address: To contact the author please send a message to his permanent email address: samuel.sandovalsolis@gmail.com